Insights in nuclei and hypernuclei production in Pb-Pb collisions with ALICE

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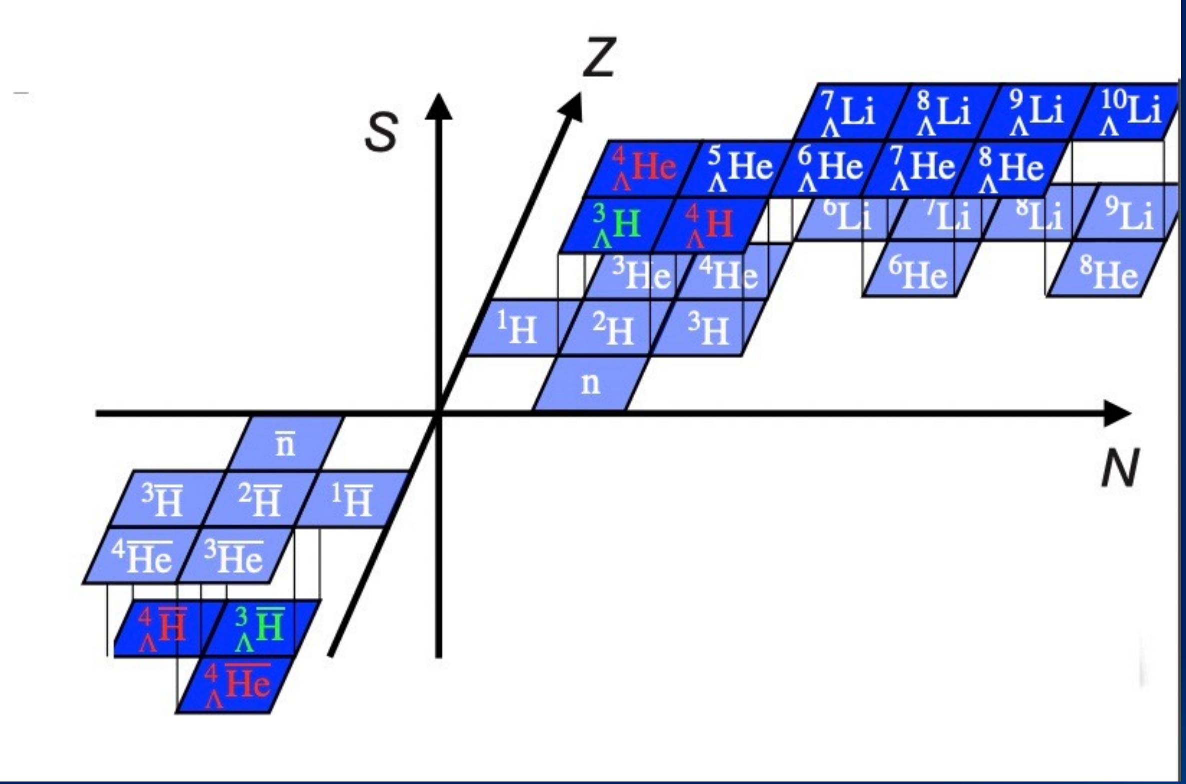
ON BEHALF OF THE ALICE COLLABORATION

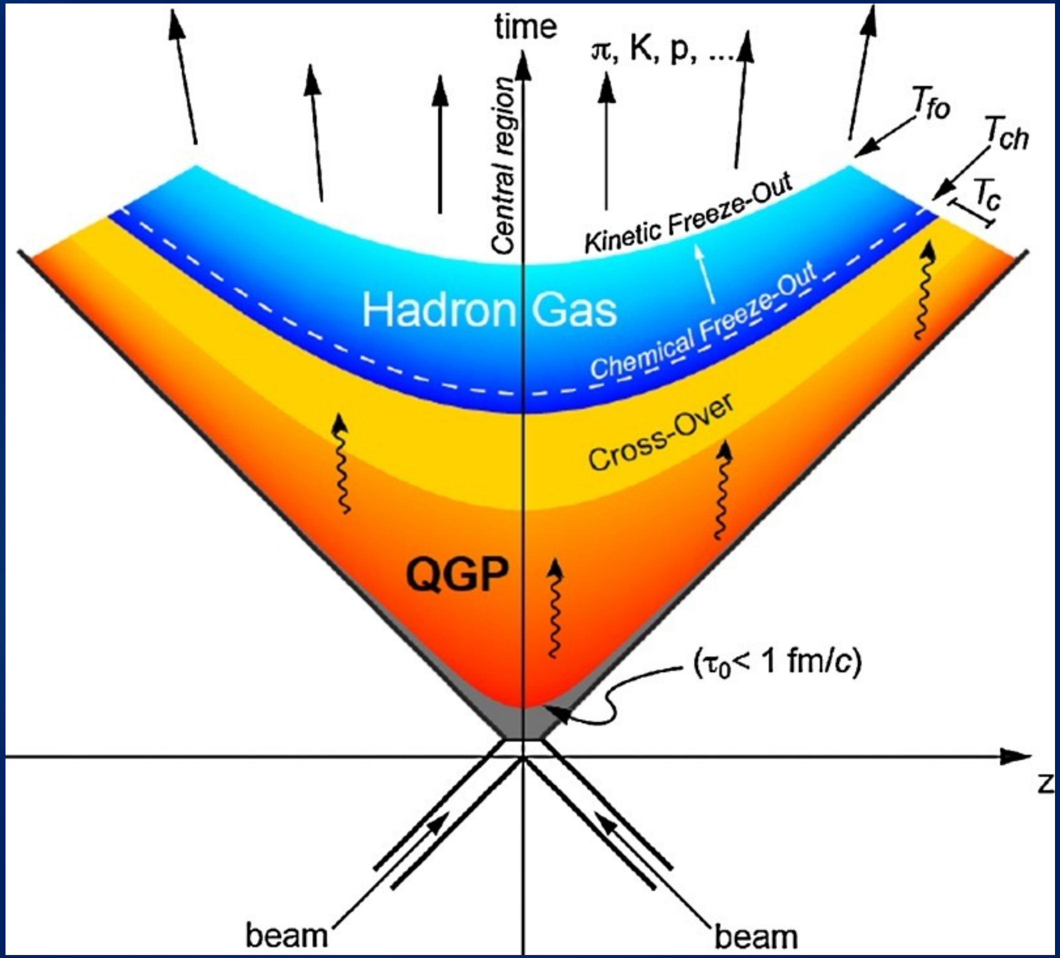
QCD@Work
International Workshop on QCD Theory and Experiment

Nuclei, Antinuclei and Hypernuclei

- Nuclei (A=2,3,4): measurements provide insights in their production mechanism
- Antinuclei : counterpart of matter, rare objects in nature, Unique probe for new exotic physics! Dark matter, antistars, …
- Hypernuclei: bound states of nucleons and hyperons (hypertriton, hyperhelium, …), testing the baryon–nucleus interactions
  - Measurements up to A=4: ${}^{4}_{\Lambda}H$, ${}^{4}_{\Lambda}He$



Heavy-Ion collision evolution

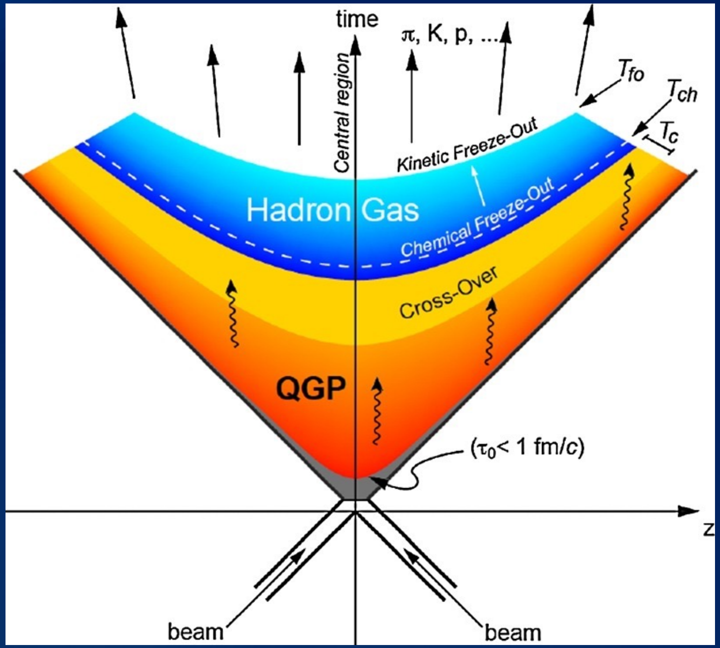


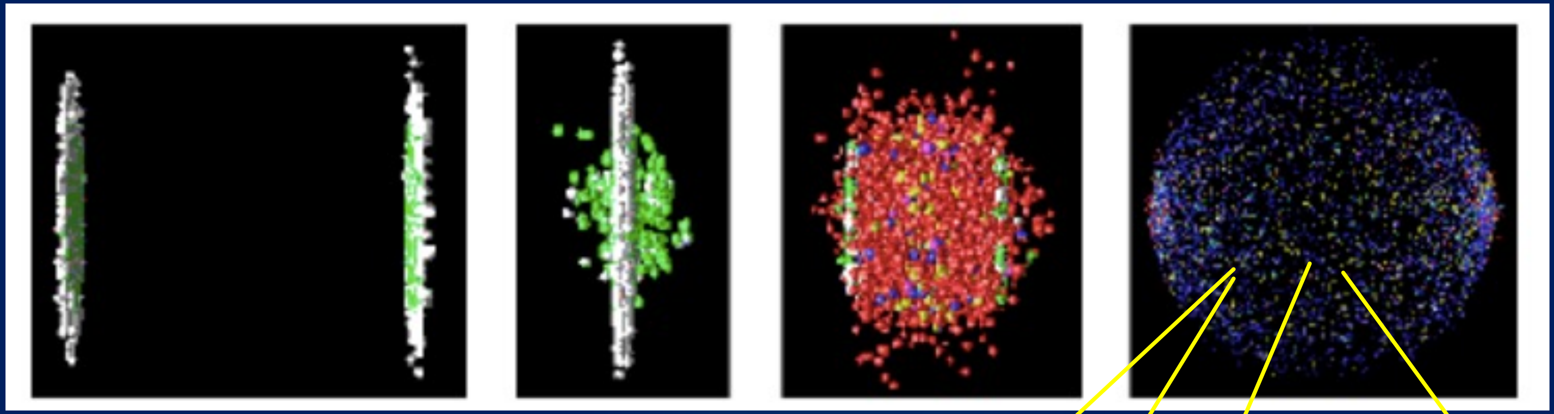
- After a pre-equilibrium time τ_0 ≈1 fm/c, a deconfined phase of quarks and gluon is created: Quark-gluon plasma (QGP)
- The system expands and cools down reaching the temperature at which hadronization takes place at the T_C = 156.5 +/- 1.5 MeV, Nucl. Phys. A 982 (2019) 847
- a phase of interacting hadrons and resonances between chemical and kinetic freeze-out, where the elastic interactions among them sieze at kinetic freeze-out Nature 561, pages321–330 (2018)
- The last elastic interactions stop at the kinetic freeze-out temperature T_{kin} (~110 MeV) 10.1103/PhysRevC.101.044907

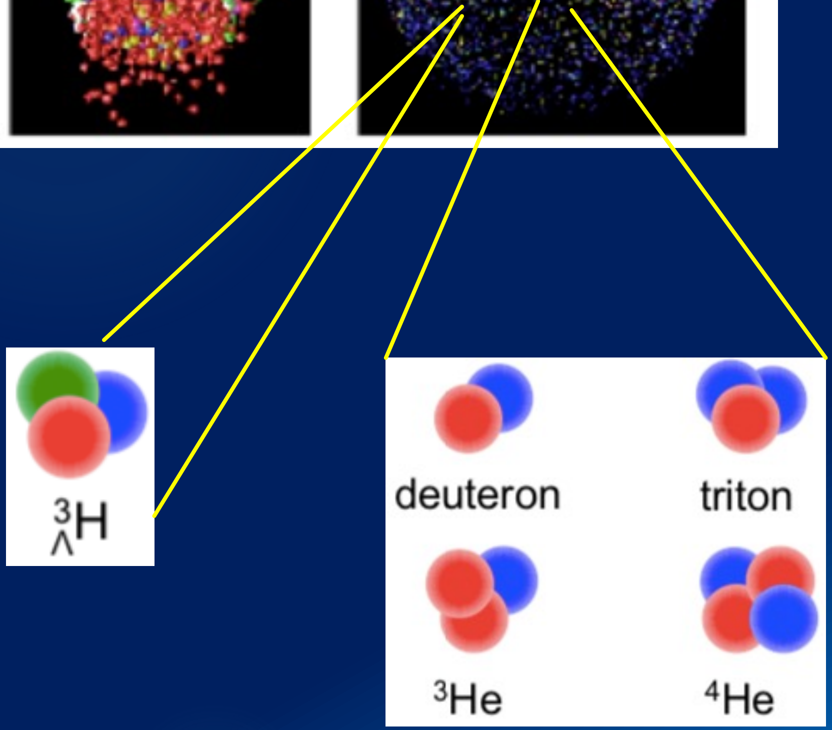
Phys. Rev. C **81**, 031902(R), Nucl. Physi. A Volume 987 (2019) Pages 144-201

Heavy-ion collision evolution

10.1016/j.nuclphysa.2019.02.006





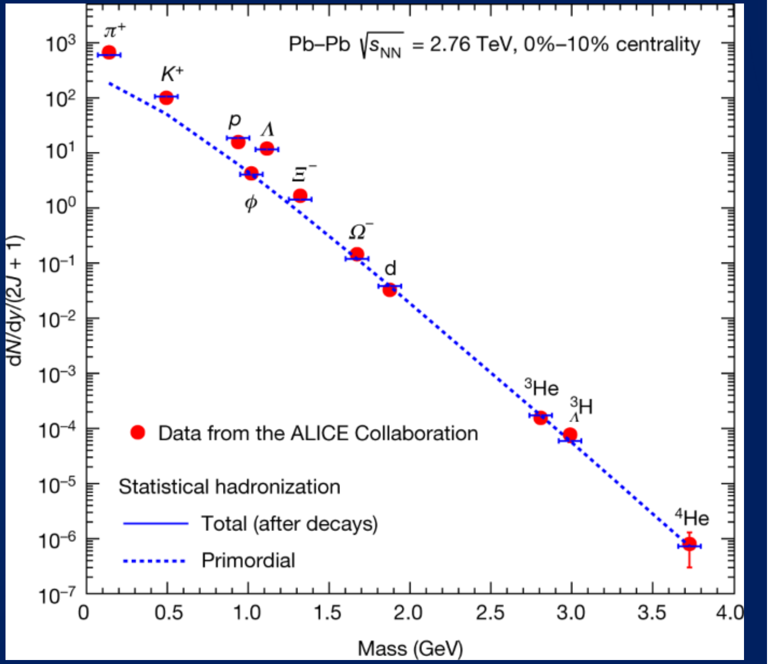


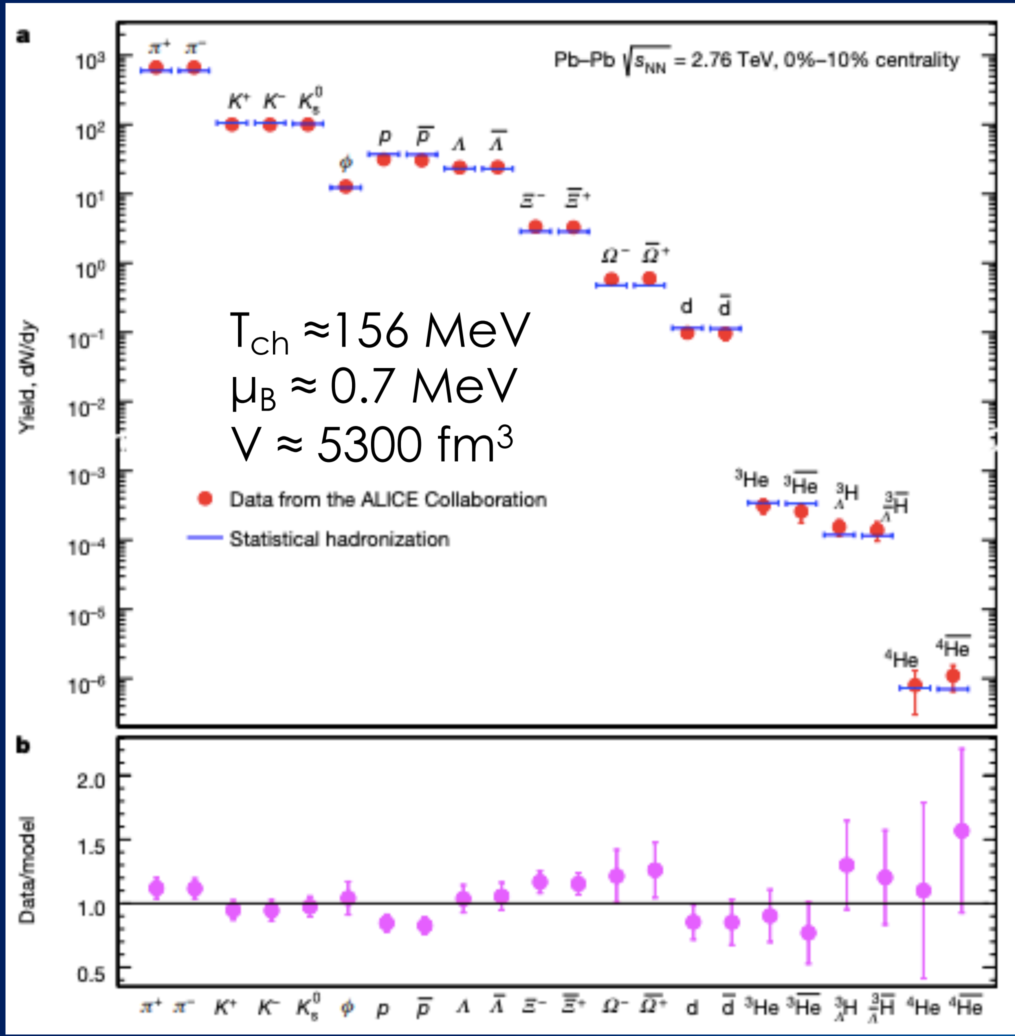
Nuclei production can be described by two models:

- Statistical Hadronization Model (SHM)
- Nucleon coalescence

Statistical Hadronization Model

- Hadrons produced in Pb–Pb collisions are well described by a grand canonical ensemble with three free parameters (μ_B, V and T_{ch})
- ALICE Pb–Pb data agree very well with Statistical Hadronization Model predictions
  - Yields ~ $\exp(-m/T_{ch})$





In small systems a canonical ensemble has to be considered (->free parameters N, V_c, T_{ch}, γ_s)

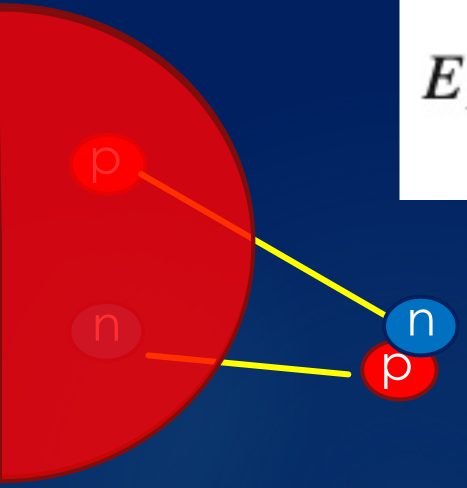
arXiv:1906.03145

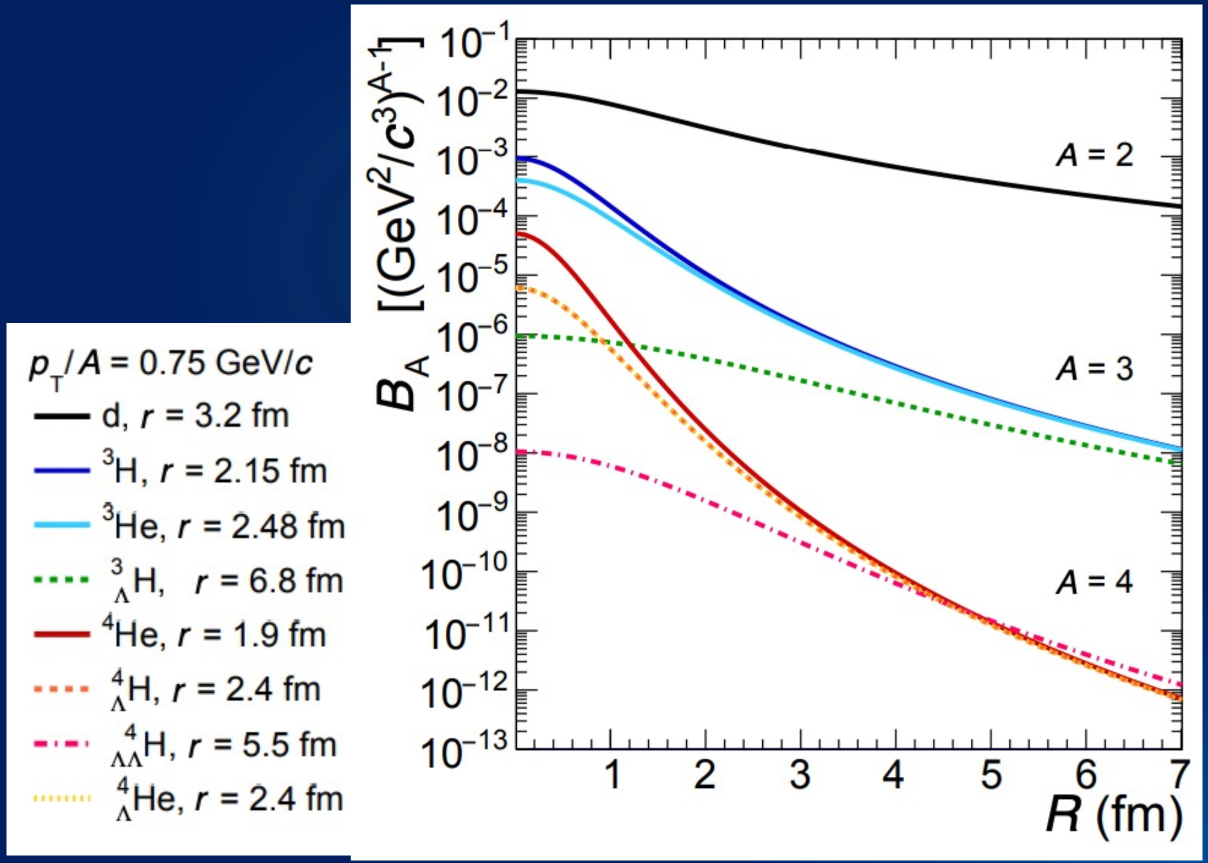
▶A. Andronic, P. Braun-Munzinger, K. Redlich, J.Stachel, Nature 561 (2018) 32

Coalescence Model

- Nuclei are formed by nucleons which are close in phase space at the kinetic freeze-out for a given nucleon mass number A $p_p = p_A/A$

$$E_A \frac{d^3 N_A}{d^3 p_A} = B_A \left(E_p \frac{d^3 N_p}{d^3 p_p} \right)^A$$

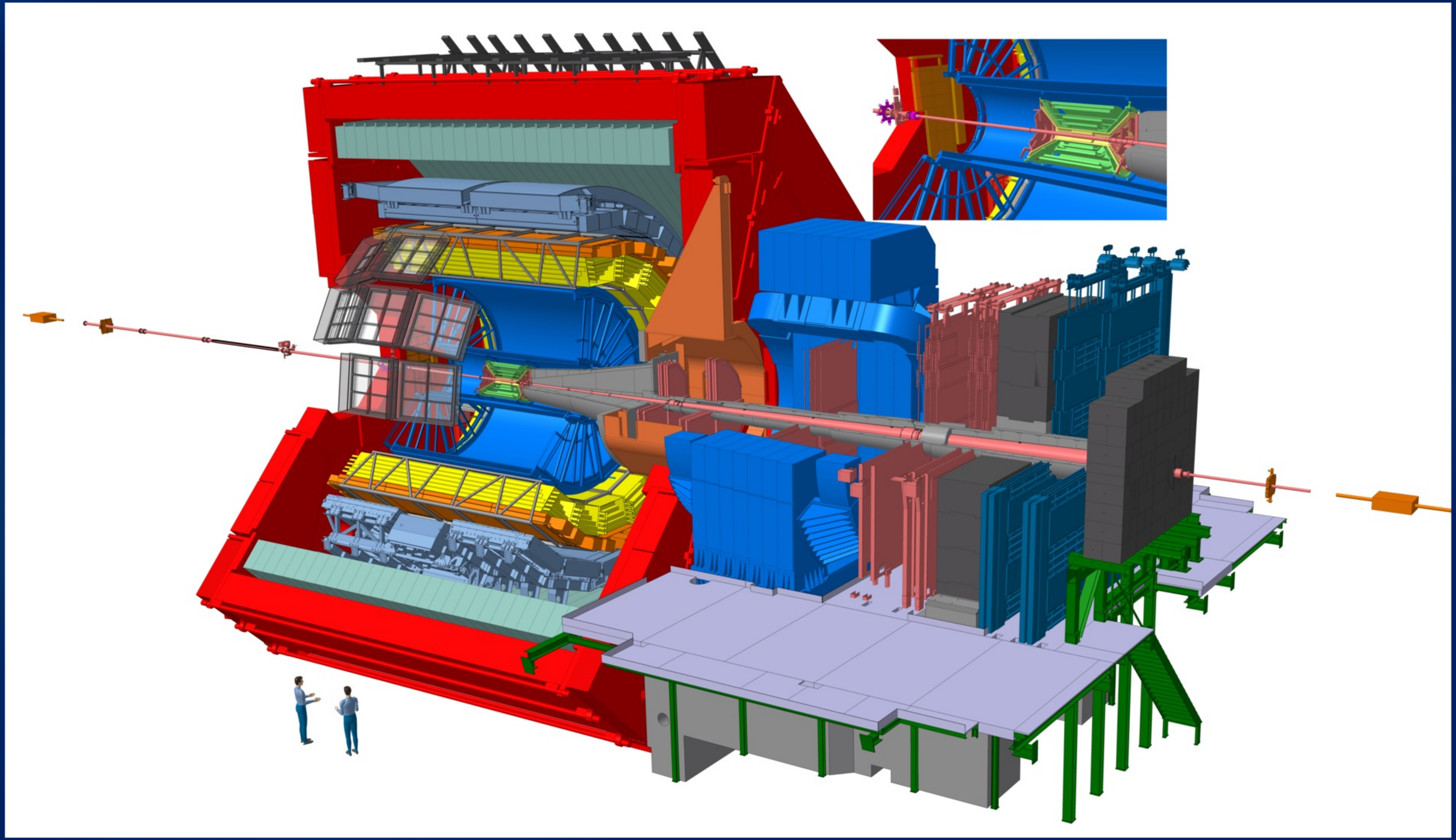




F. Bellini, and A. Kalweit, Acta Phys. Pol. B 50 (2019) 991

- Coalescence parameter B_A is the crucial parameter
  - probability for A nucleons to bind together forming a nucleus of mass number A
  - simple coalescence scenario foresees it is not dependent on p_T and muliplicity -> contradiction by measurements

The ALICE Detector



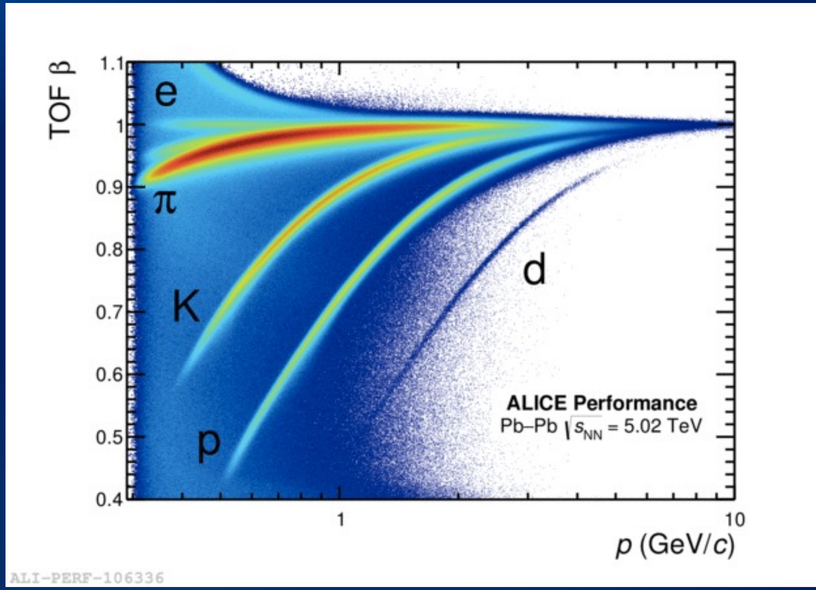
Inner Tracking System (ITS):
- Tracking & Vertexing
  - σ_{DCAxy} < 100 μm at p_T>500 MeV/c

Time Projection Chamber (TPC):
- Tracking & Vertexing
- PID via dE/dx (≈6%)

Time-of-Flight (TOF) PID
- π/K separation up to 3 GeV/c
- K/p separation up to 4.5 GeV/c

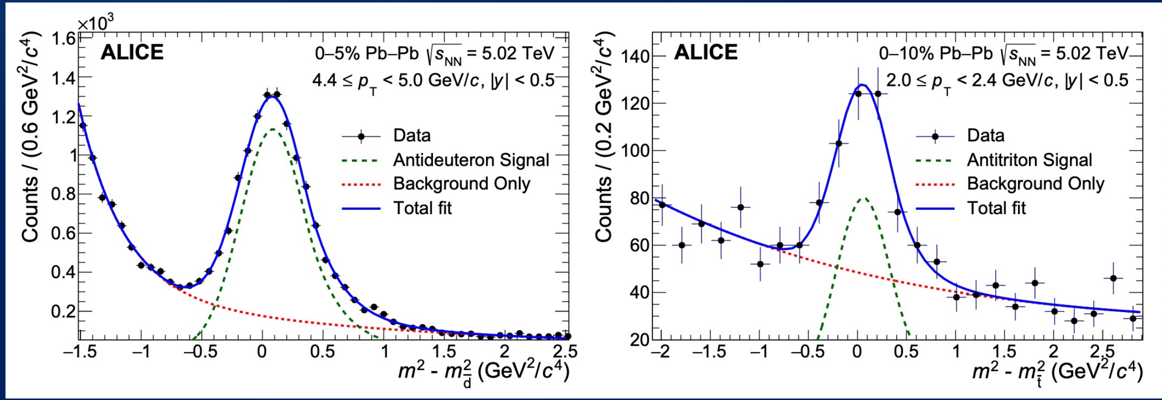
V0 :
- Centrality/multiplicity determination
- trigger

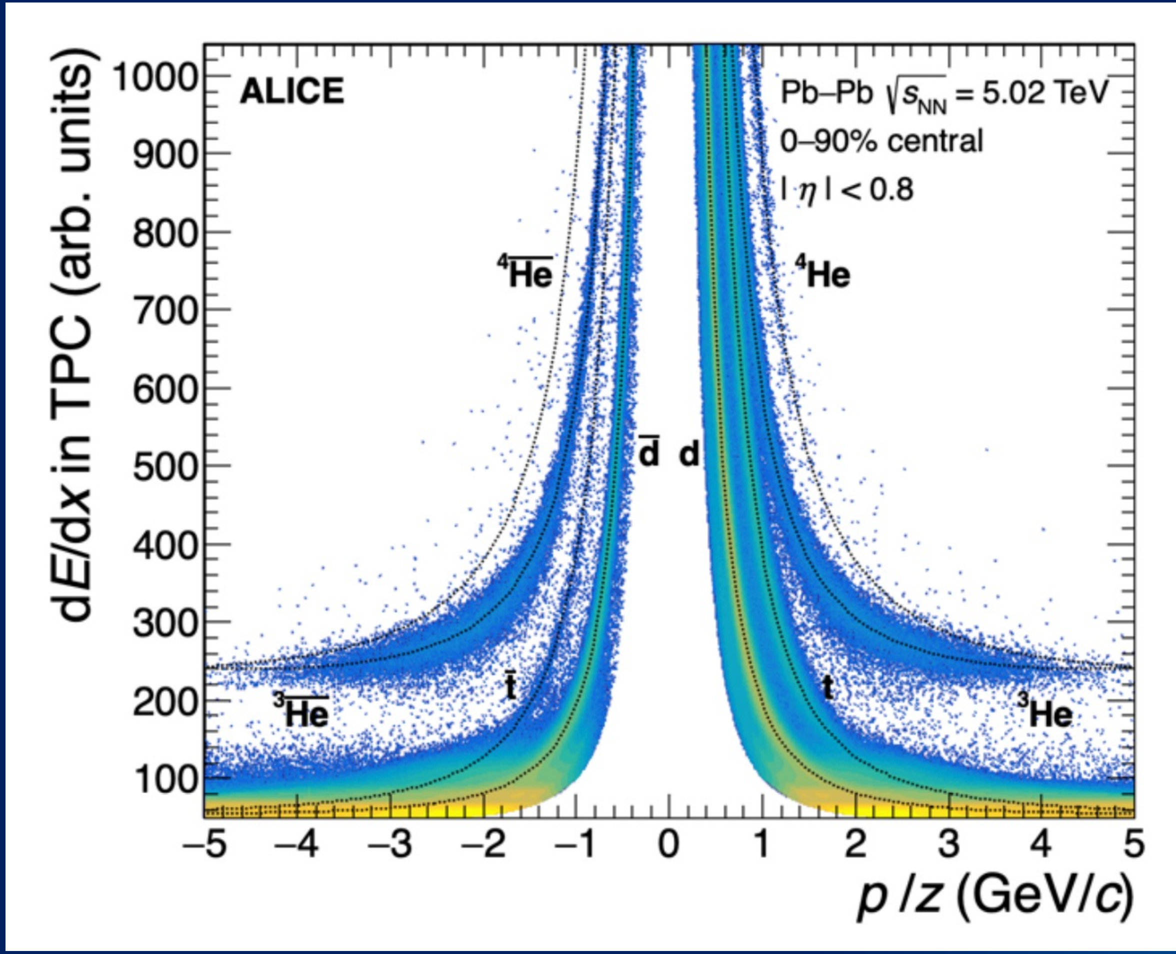
(Anti)Nuclei identification



- $m^2 = \frac{(1-\beta^2)}{\beta^2} p^2$
- $\beta = \frac{L}{t_{TOF} c}$

https://doi.org/10.1103/PhysRevC.107.064904



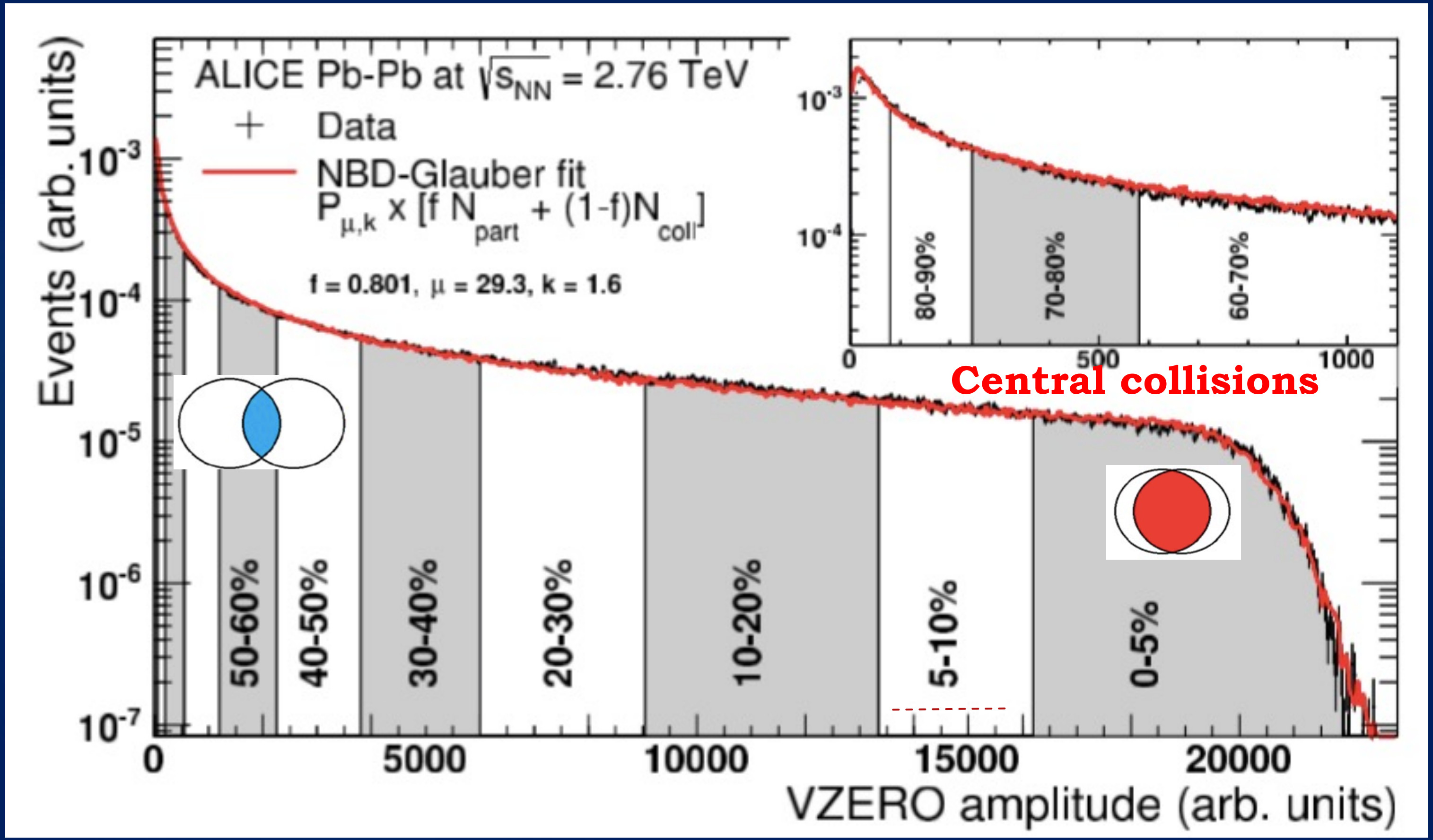


Phys. Rev. C 107, 064904

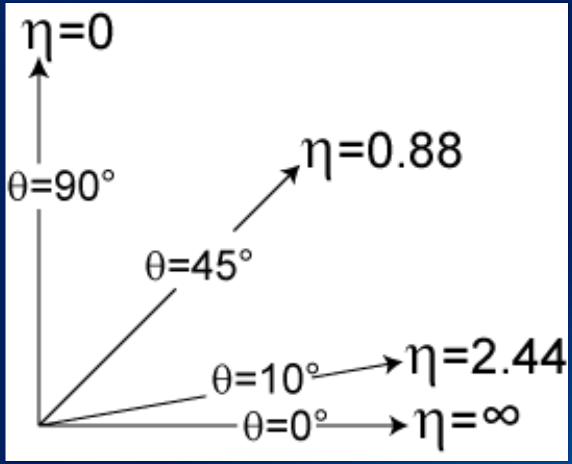
Centrality

- The number of produced particles at midrapidity increases with centrality

Phys. Rev. C 88, 044909

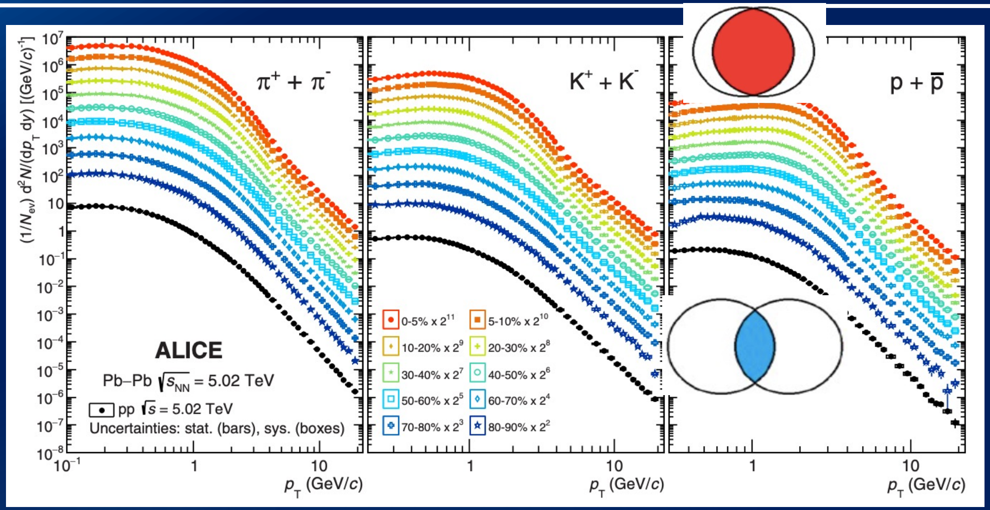


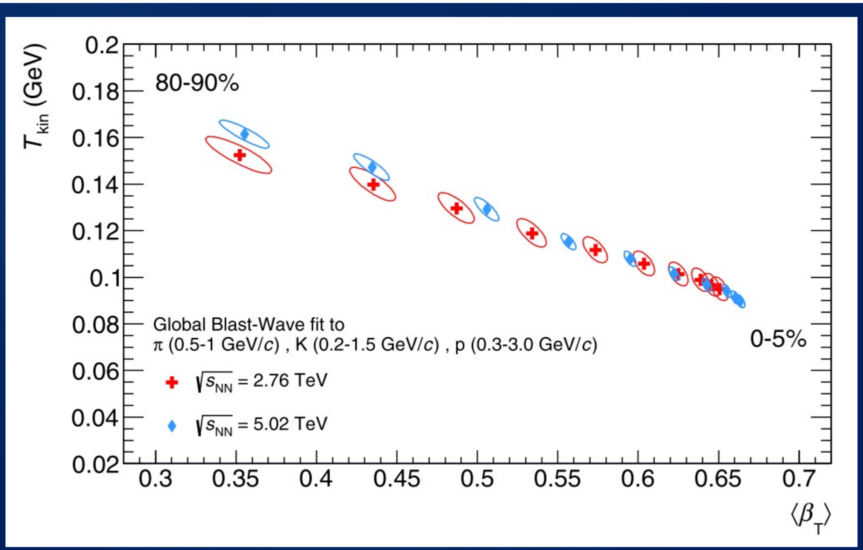
TPC/TOF



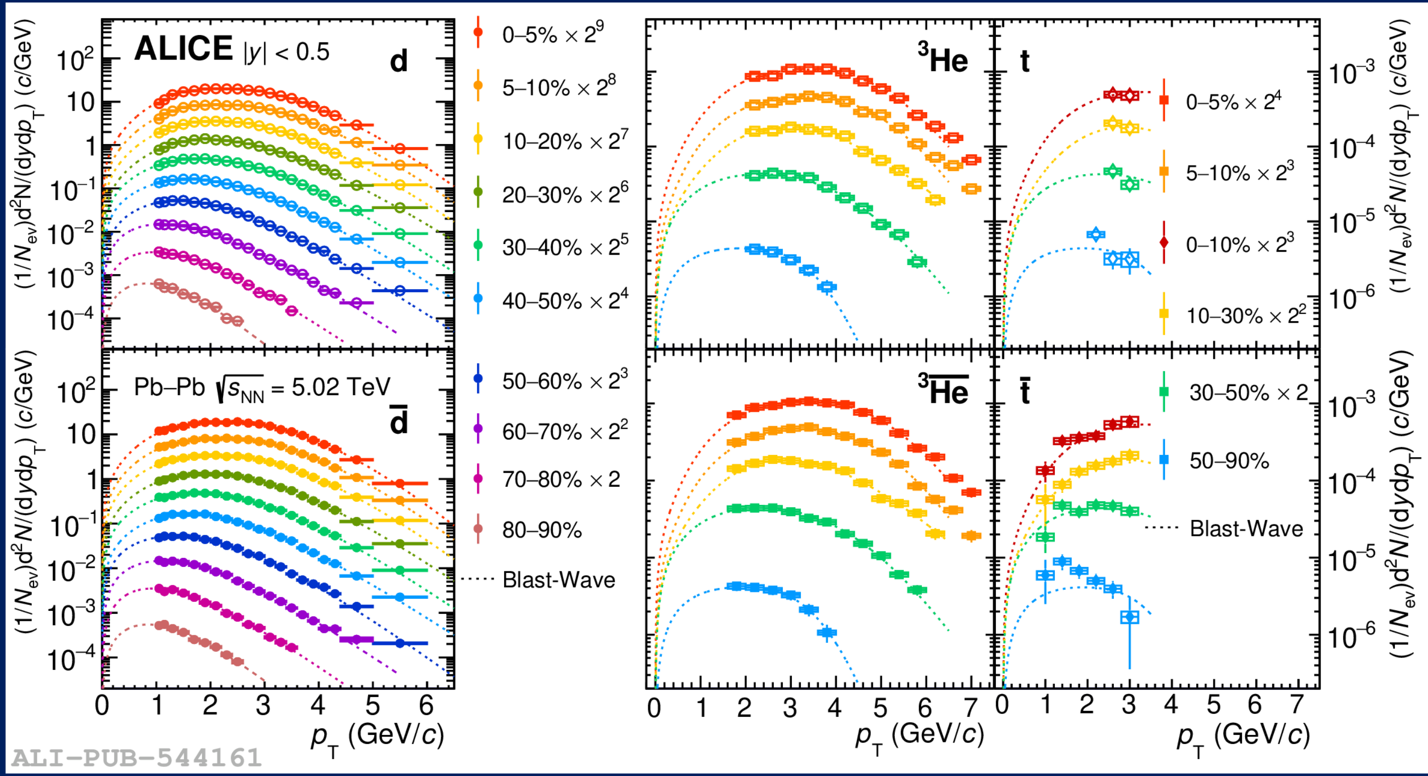
V0

hadron spectra : kinetic freeze out





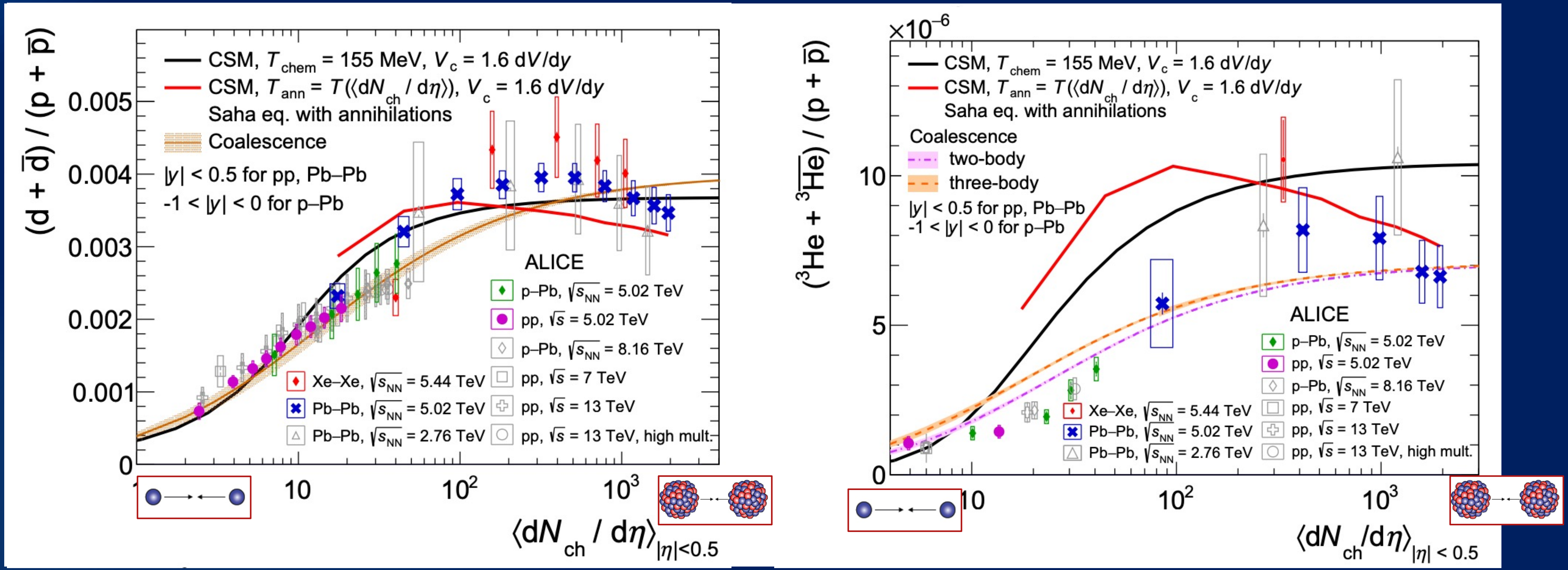
Phys. Rev. C 101, 044907



Phys. Rev. C 107, 064904

Blast wave model: light hadrons are emitted by an expanding source at a temperature T_{kin} and show a collective motion given by a radial flow $<\beta_T>$
$\Rightarrow$ Hardening of the spectra from peripheral to central collisions

Light nuclei production vs $dN_{ch}/d\eta$



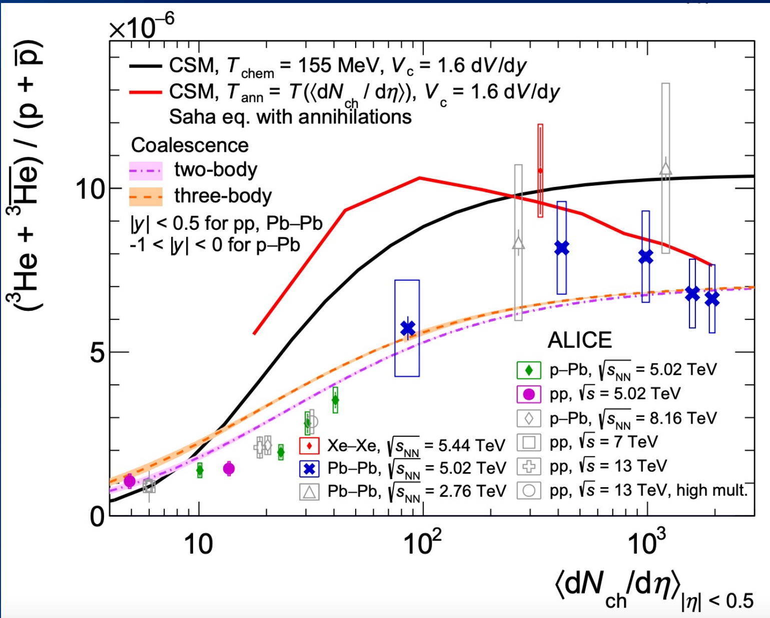
light nuclei as probes of the production mechanisms

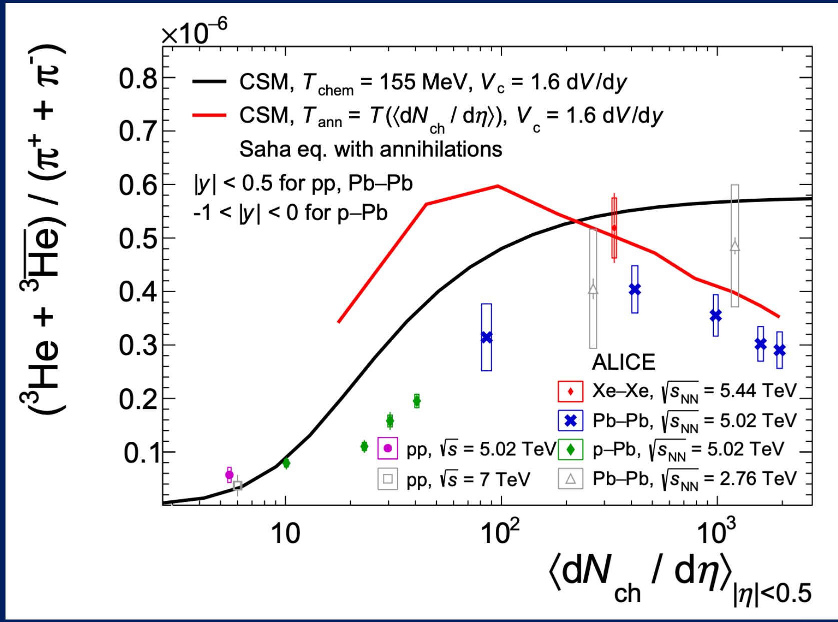
Smooth evolution of d/p and 3He/p ratios with the system size

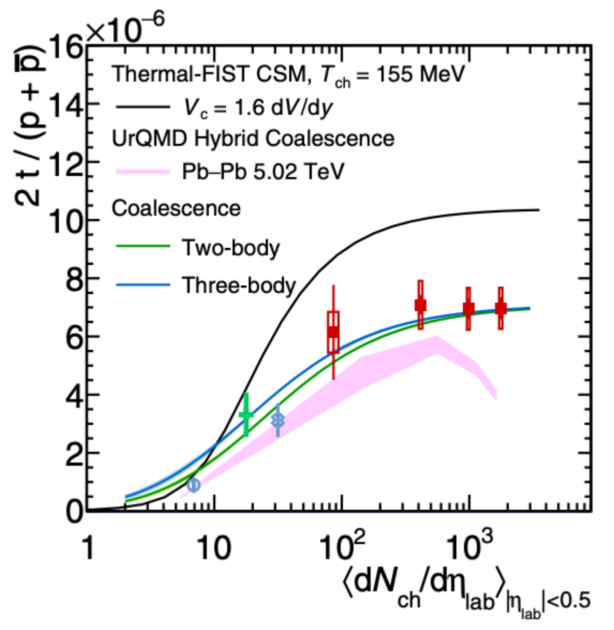
arXiv:2405.19826

A=2 : multiplicity dependence is well reproduced by both CSM and coalescence
A=3 : ratio fairly described by the coalescence approach at low and high charged-particle multiplicity densities. Tension at intermediate (10-40) multiplicities

Production models : A=3





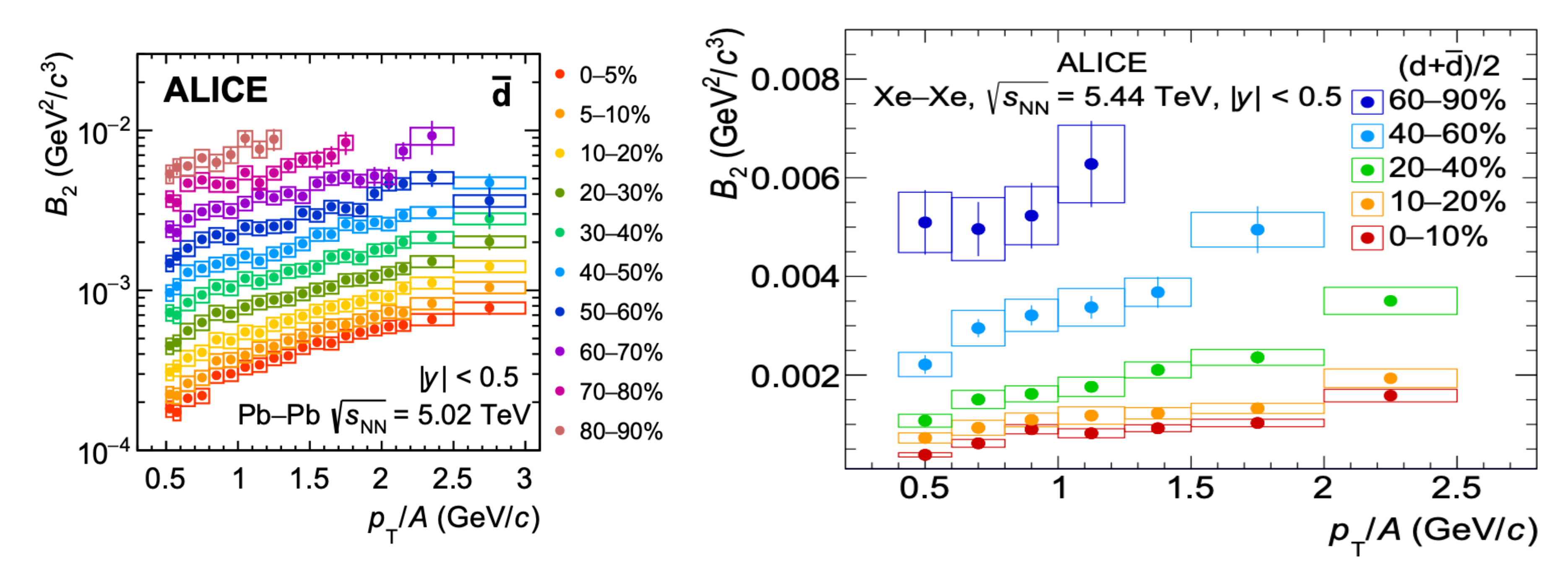


arXiv:2405.19826

Phys Rev C 107, 064904 (2023)

Production of nuclei with *A*=3 tests the models !
CSM and coalescence predictions do not reproduce the trend of the ratios
Tension at intermediate multiplicities (10 – 40)

Coalescence parameters vs p_T: A=2



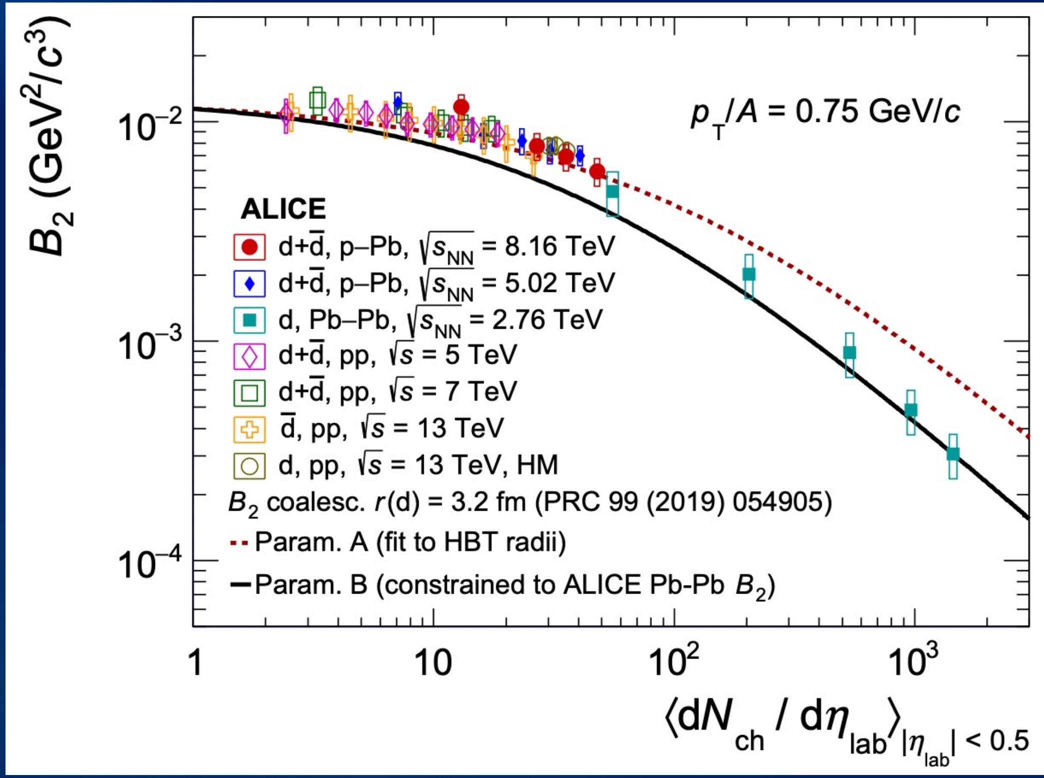
$$B_A = \frac{E_A \frac{d^3N_A}{d^3p_A}}{\left(E_p \frac{d^3N_p}{d^3p_p}\right)^A}$$

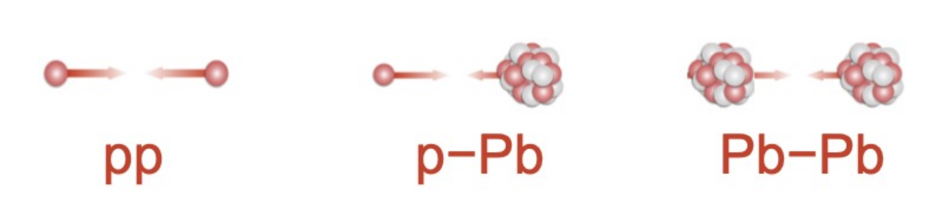
Phys Rev C 107, 064904 (2023)

arXiv:2405.19826

- Ordering of the coalescence parameters with collision centrality:
  - *B_A decreases if centrality increases*
  - If centrality increases, then also the *R* of the source increases (peripheral to central events)
  - Bigger *R* implies a larger separation between nucleons => in the coalescence scenario this environment reduces coalescence probability

Coalescence parameter vs $dN_{ch}/d\eta$: B_2



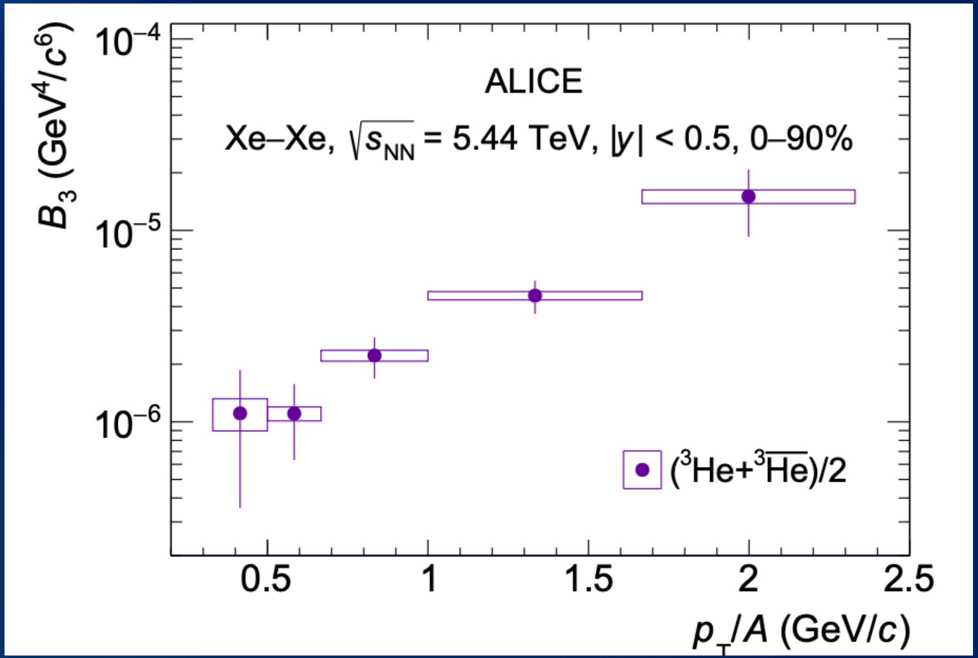


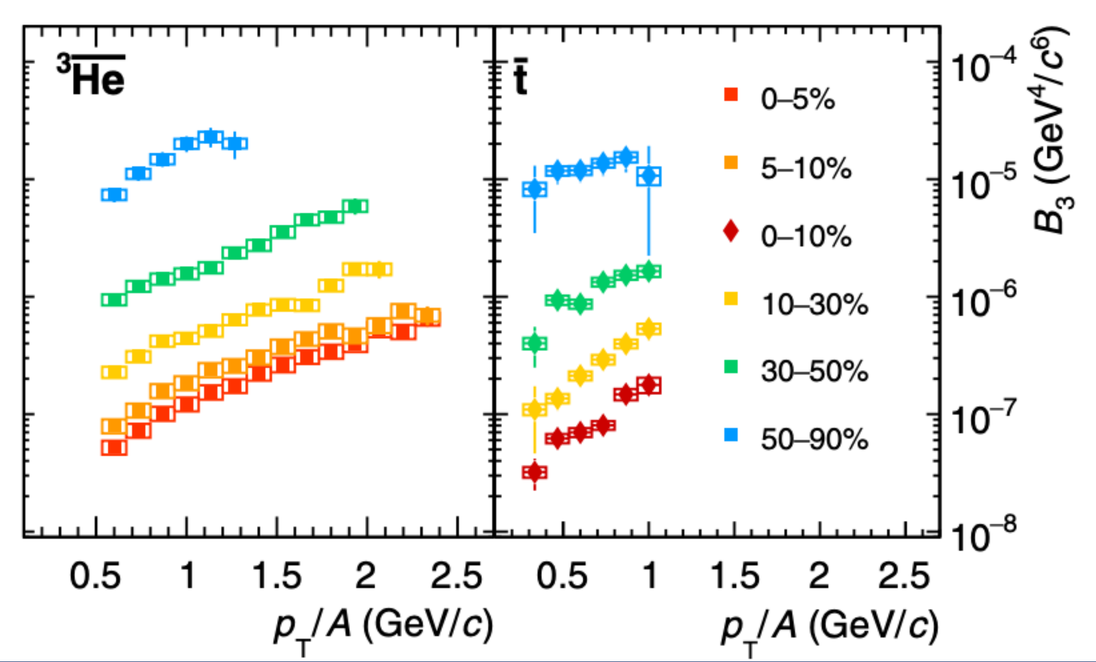
B_A: quantifies the probability for A nucleons to bind together forming a nucleus of mass number A

the dominant production mechanism:
- evolves smoothly as a function of the system size
- is independent of the collision system and center-of-mass energy

Larger system sizes lead to enhanced space separation between nucleons => decrease of B_A

Coalescence parameter vs p_T: B_3

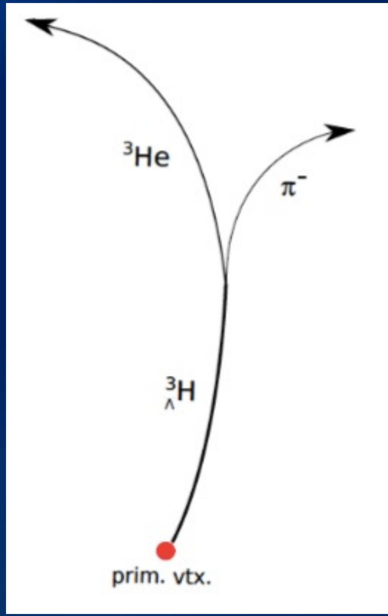




- B_A raises with p_T
  - It points to the fact that high p_T particles originate from a smaller region of the source
- Two possible ways to form A = 3 nuclei
  - three nucleons (called three-body coalescence)
  - formation of the nucleus from a deuteron and a nucleon (two-body coalescence)

Further test with hypernuclei!

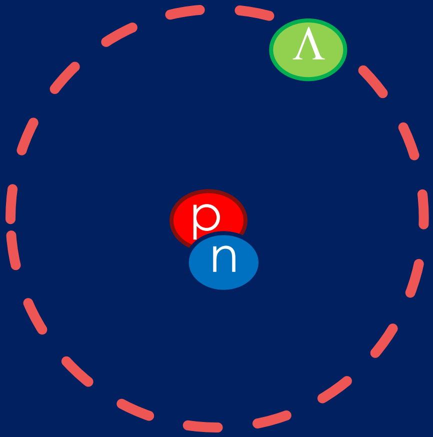
Hypernuclei : Hypertriton



$$^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$$
$$^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{H} + \pi^{0}$$
$$^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^{-}$$
$$^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{n} + \pi^{0}$$

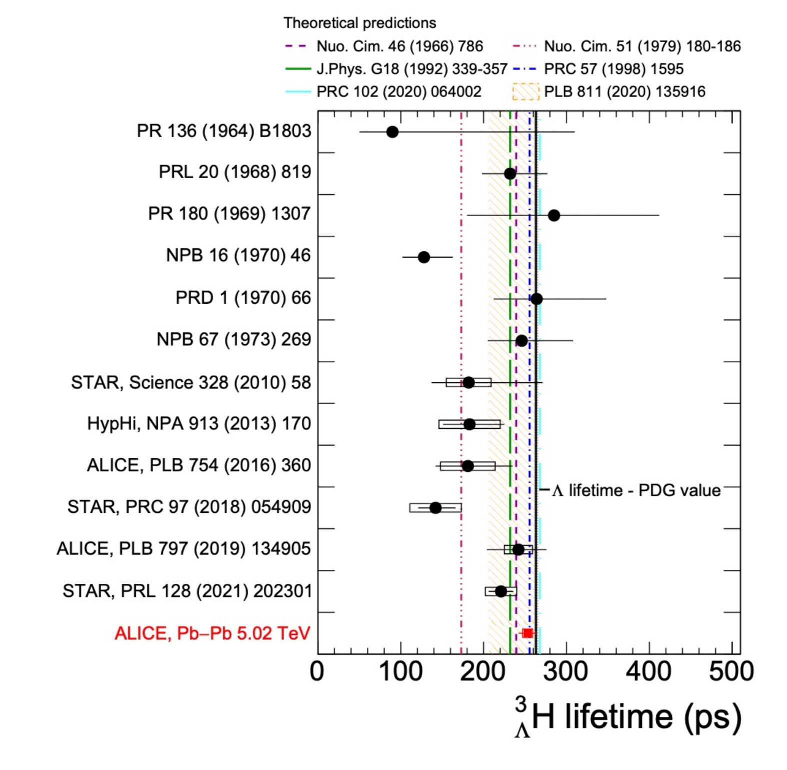
+ charge conjugates

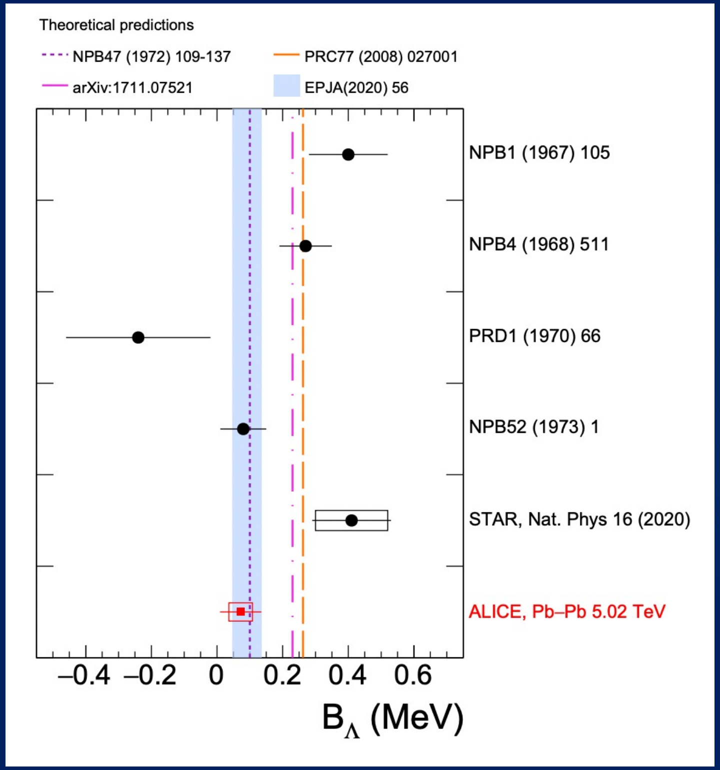
- m = 2.991 GeV/c^2
- B_Λ = 130 keV
- Radius for the hypertriton wave function $r_{\Lambda\text{-}d} \approx$ 10 fm   Phys. Rev. C 100, 034002 (2019)
- Fragile object



- In pp collisions the size of the produced medium is much smaller than the Hypertriton nucleus
- Coalescence is sensitive to the interaction volume as well as the size of the nucleus
- The ratios $^{3}_{\Lambda}$H/^{3}He or $^{3}_{\Lambda}$H/Λ probe nuclear production mechanisms!

Hypertiton Lifetime measurements



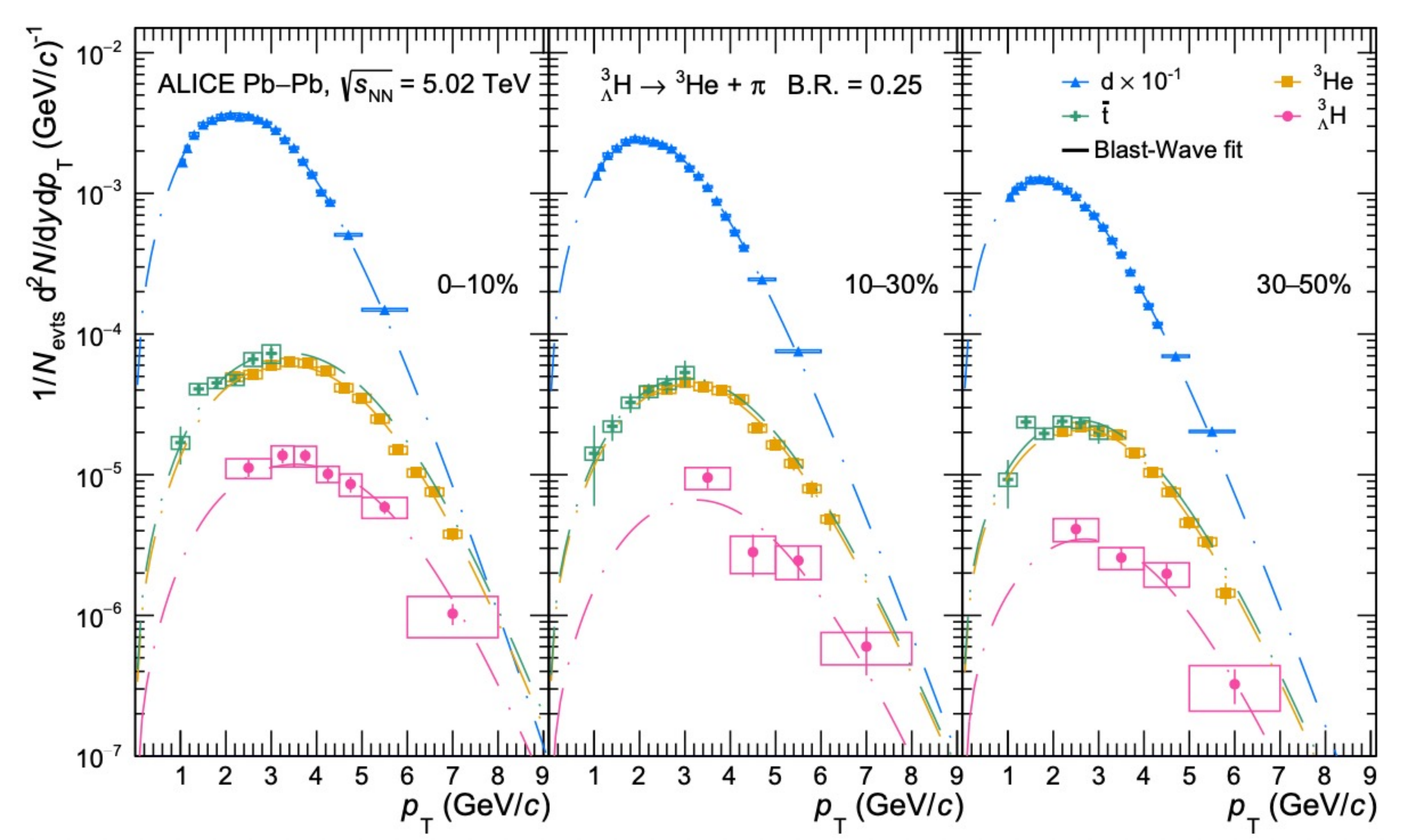


The most precise measurements to date of the $^{3}_{\Lambda}$H lifetime τ and Λ separation energy B_{Λ} are obtained using the data sample of Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV collected by ALICE at the LHC.

arXiv:2209.07360

- Hypertriton lifetime measured by ALICE is compatible with the free Λ lifetime within its uncertainties
- It confirms it is a very loosely-bound state

Hypernuclei spectra : kinetic freeze out



arXiv:2405.19839

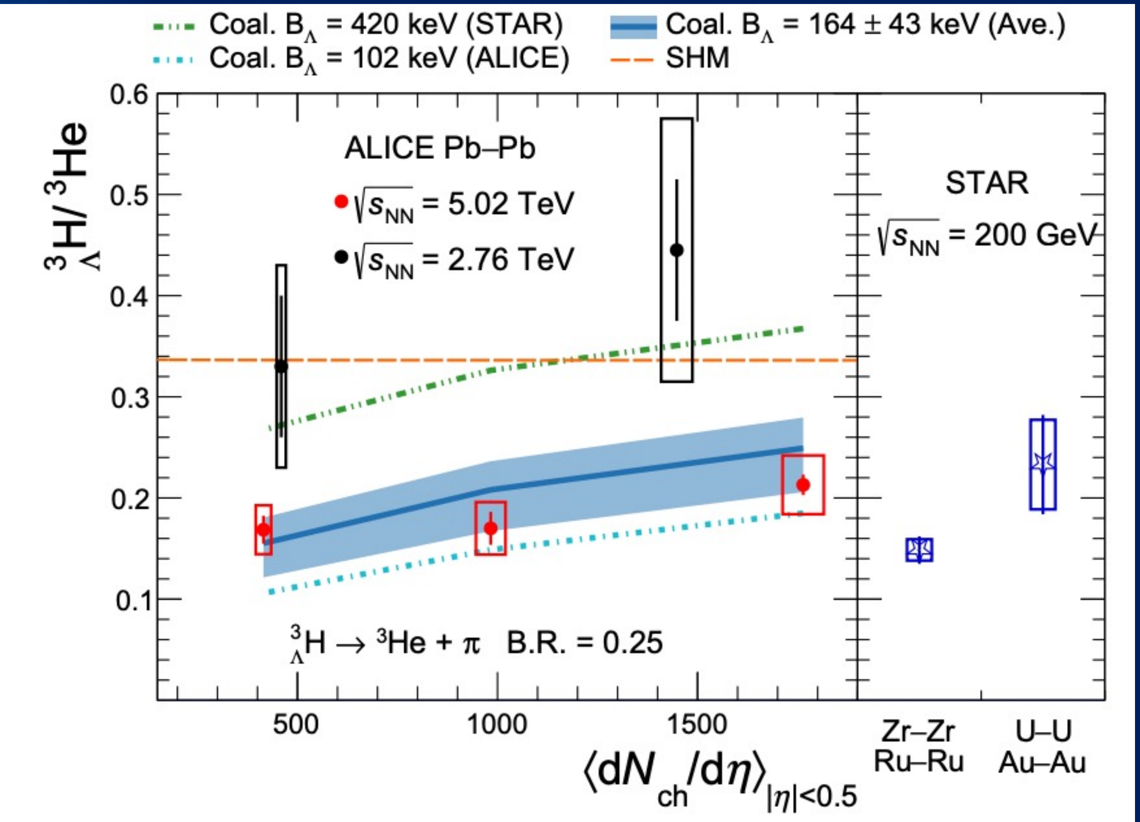
Centrality	$\langle \beta_T \rangle$	T (GeV)
0–10%	0.694 ± 0.003	0.103 ± 0.005
10–30%	0.666 ± 0.003	0.132 ± 0.008
30–50%	0.598 ± 0.005	0.152 ± 0.010

The fit temperature and velocity profiles are compatible with other light-flavoured nuclei

common kinetic freeze-out surface for hypernuclei and ordinary nuclei

SHM and coalescence tested via the $^{3}_{\Lambda}H/^{3}He$ and $^{3}_{\Lambda}H/\Lambda$ as a function of multiplicity -> see next slides!

$^{3}_{\Lambda}H$ ratios vs multiplicity

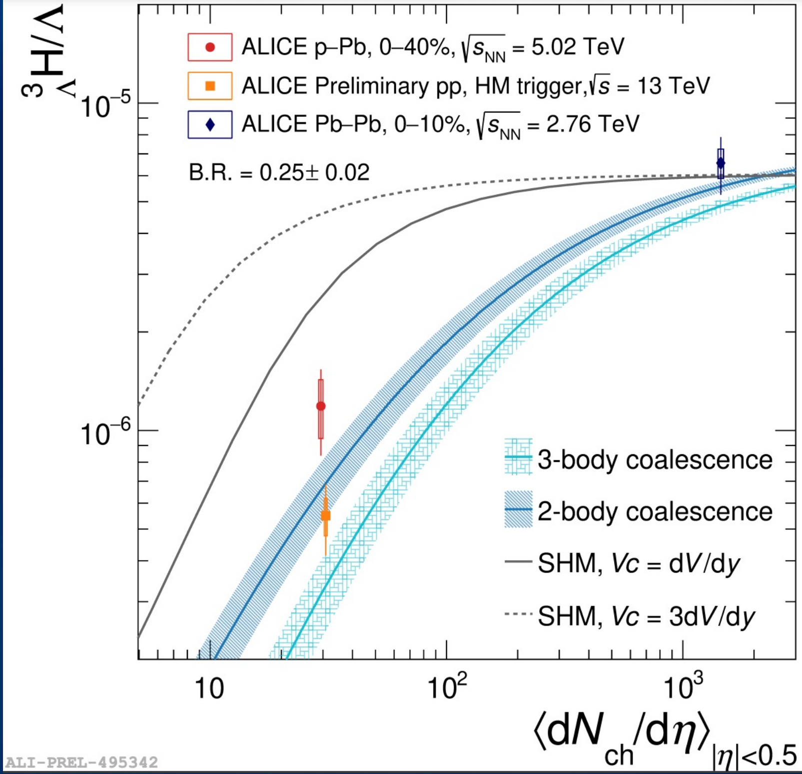


In SHM model the masses count in the final hadron yields ($^{3}_{\Lambda}H$ mass =2.991 GeV/c^2 and ^{3}He mass =2.809 GeV/c^2) => within high multiplicity events SHM predictions are flat

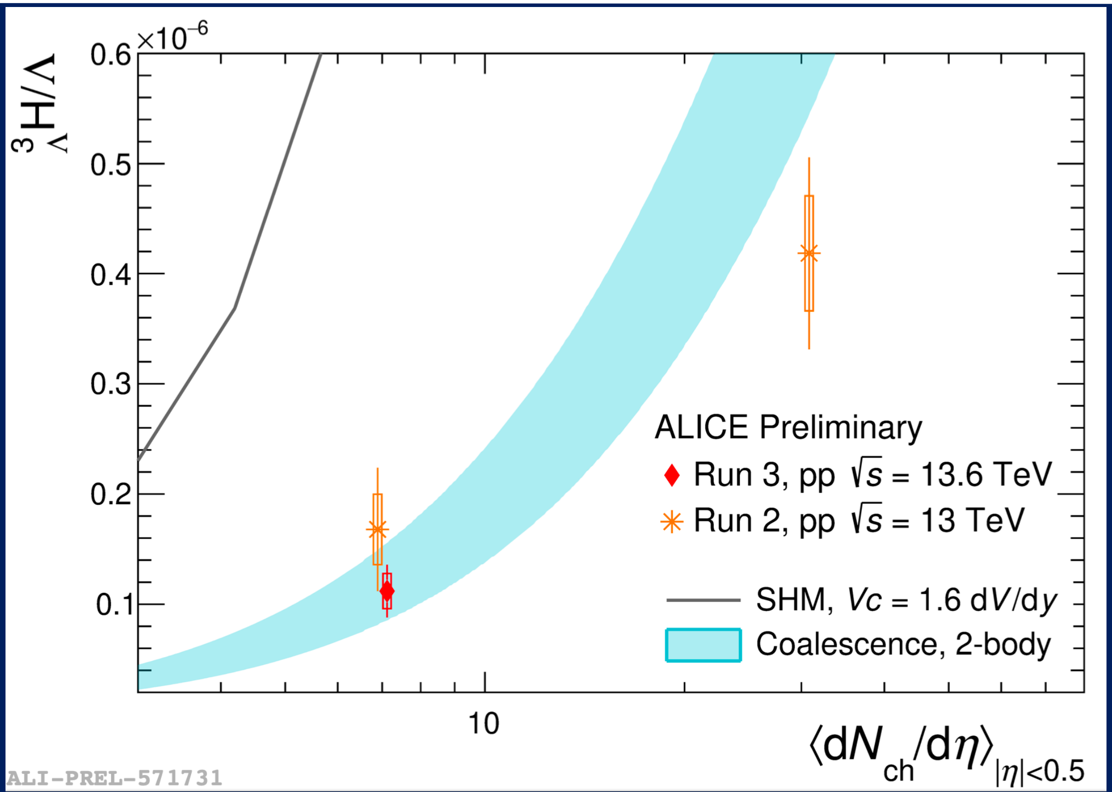
coalescence is sensitive to the interplay between the spatial extension of the nucleus wavefunction and the system size

Coalescence describes the hypertriton production better

$^{3}_{\Lambda}H$ / Λ ratio vs multiplicity



Phys. Rev. Lett.128 (2022) 252003

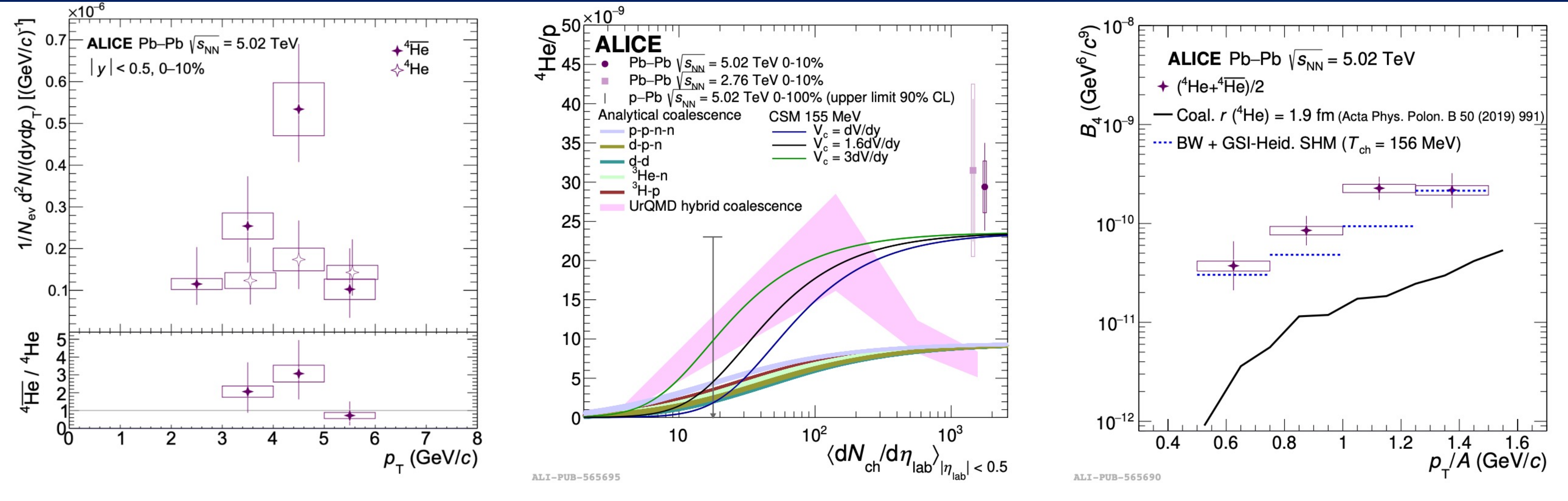


2-body coalescence favoured -> need more data at intermediate multiplicities

- Coalescence and statistical hadronization model predictions converge at heavy-ion collision multiplicities (-> large source size at central heavy-ion collisions => less discriminating power)
- The ratio is sensitive to the nuclei production mechanism at low multiplicities
- In a coalescence picture the production in small systems is more suppressed compared to SHM. ->Interplay between nuclei and source size in coalescence model whereas size of the nuclei is not considered in SHM

ALICE measures A=4 in Pb-Pb collisions

- SHM predicts in Pb-Pb a penalty factor 300 when adding one nucleon
  - $^3He/^4He = 2.70 \cdot 10^{-3}$ (see arXiv:1010.2995)
  - ^4He very stable and compact wrt previous nuclei : $E_B \sim 28$ MeV, r ~ 1.7 fm

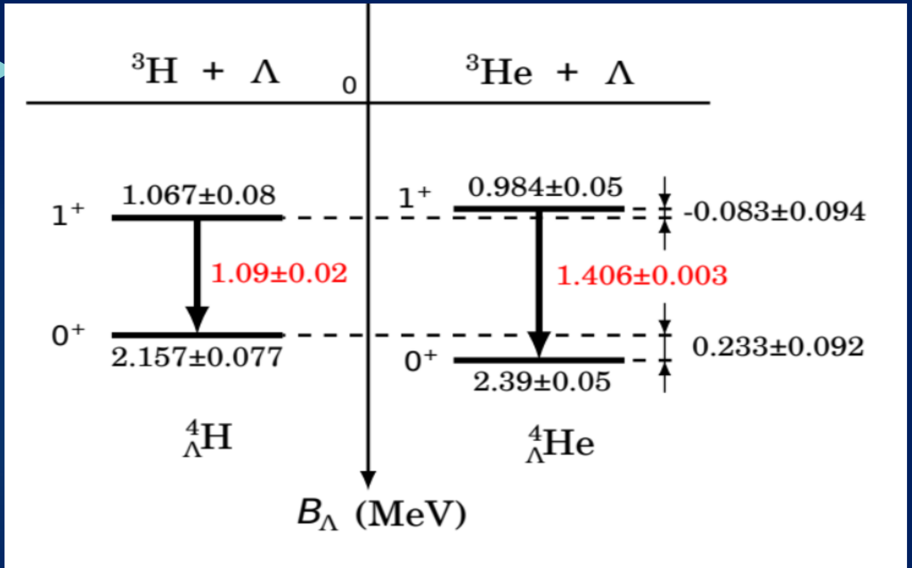


data needed at intermediate multiplicity to disentagle the different models

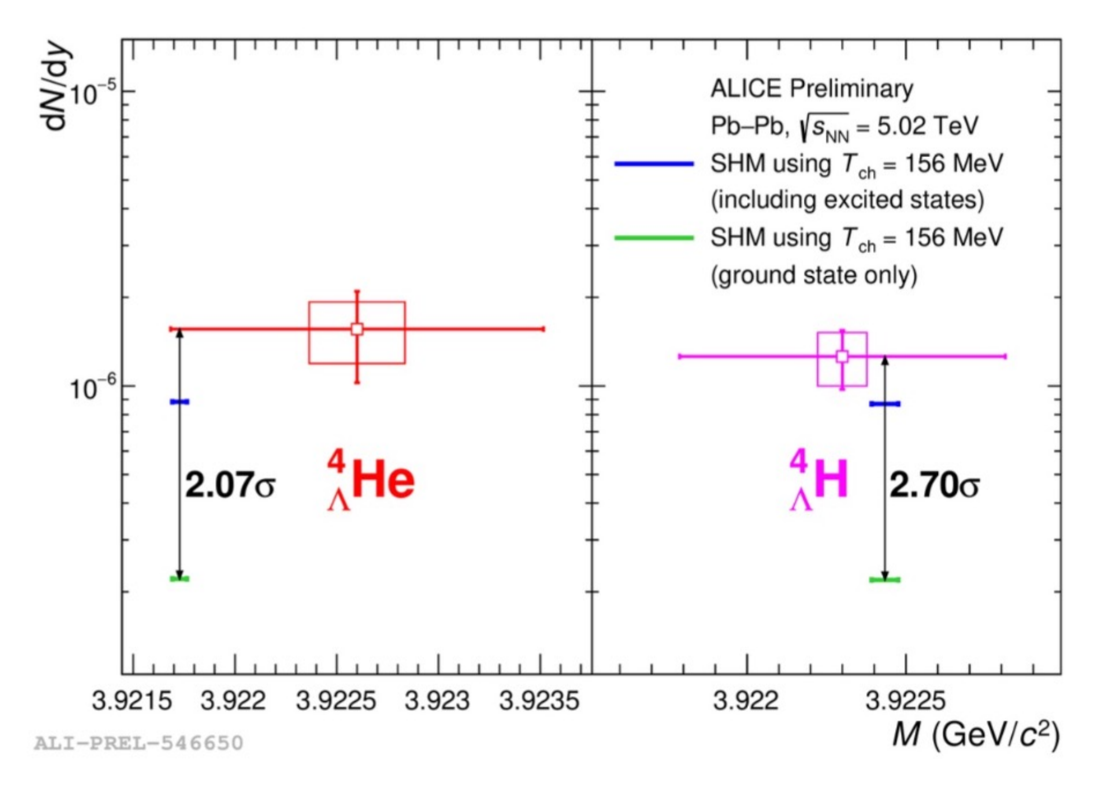
arXiv:2311.11758

ALICE MEASURES A=4 Hypernucleus

- SHM predicts a penalty factor 300
- Factor 4 increase due to feeddown from excited states of ${}^4_\Lambda$H and ${}^4_\Lambda$He



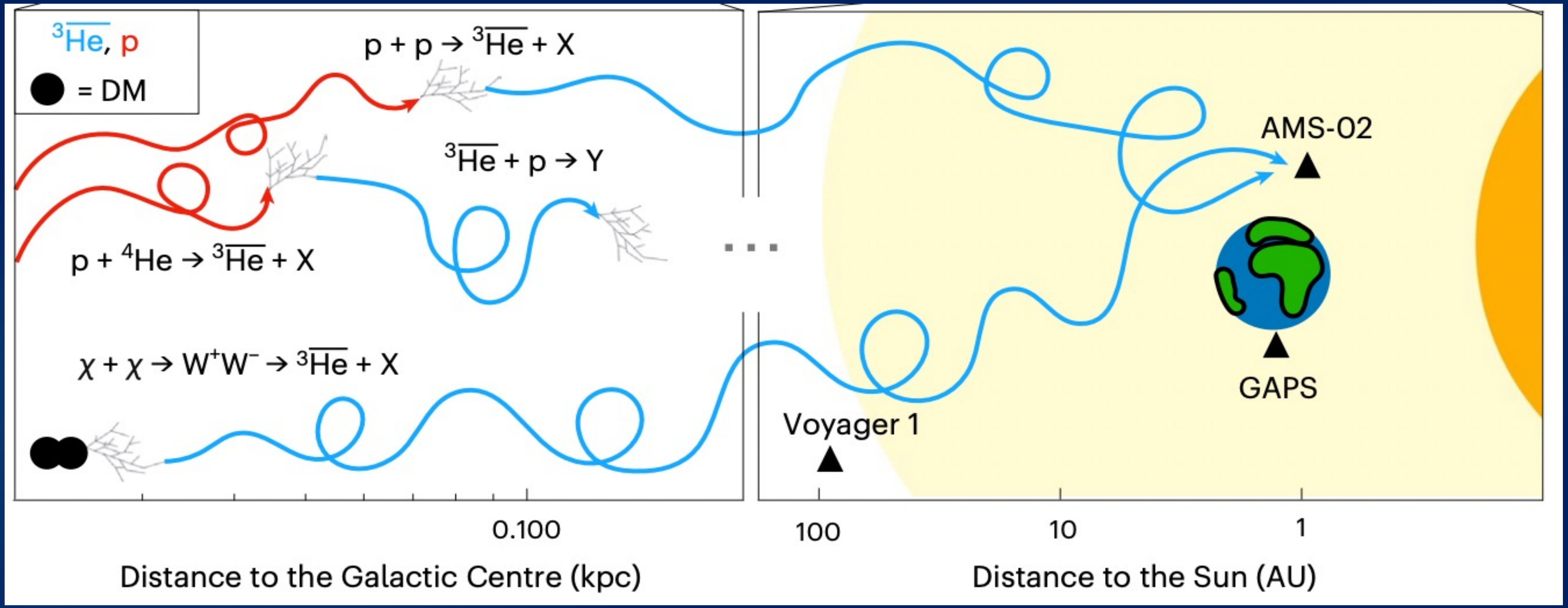
EPJ Web Conf. 276 (2023) 04002
https://hypernuclei.kph.uni-mainz.de/



- Agreement with the presence of excited states. → More in high statistics Run 3 data !!

Antinuclei as probes of Dark Matter

- Studies on the annihilation of antinuclei to determine the inelastic cross section of $^{3}\overline{He}$ -> Probes of Dark Matter



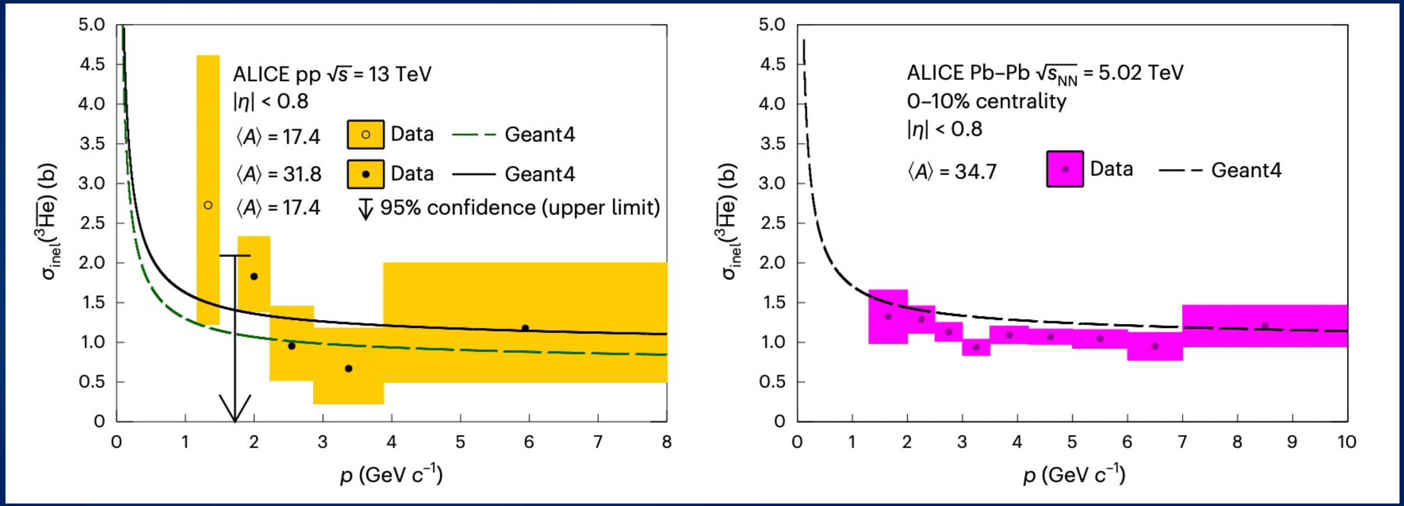
Nature Physics 19, pages 61–71 (2023)

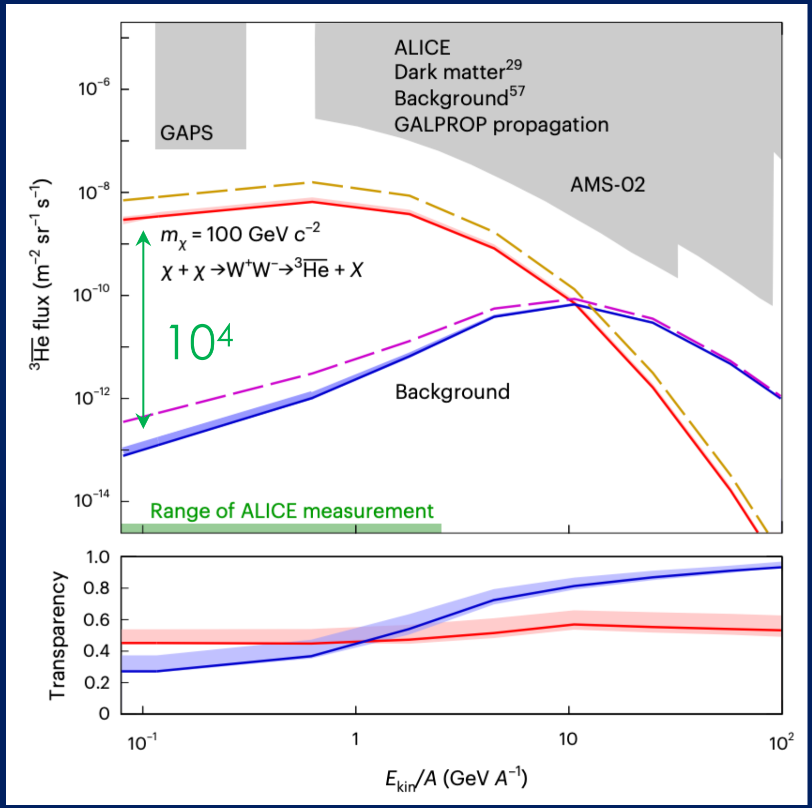
- Antinuclei sources : Dark Matter, cosmic-ray interactions with interstellar medium

https://doi.org/10.1038/s41567-022-01804-8

Antinuclei as probes of Dark Matter

- At low energies $\overline{^3He}$ the transparency of our Galaxy is about 50% if they are created by a DM source and about 25% if they come from cosmic-ray interactions



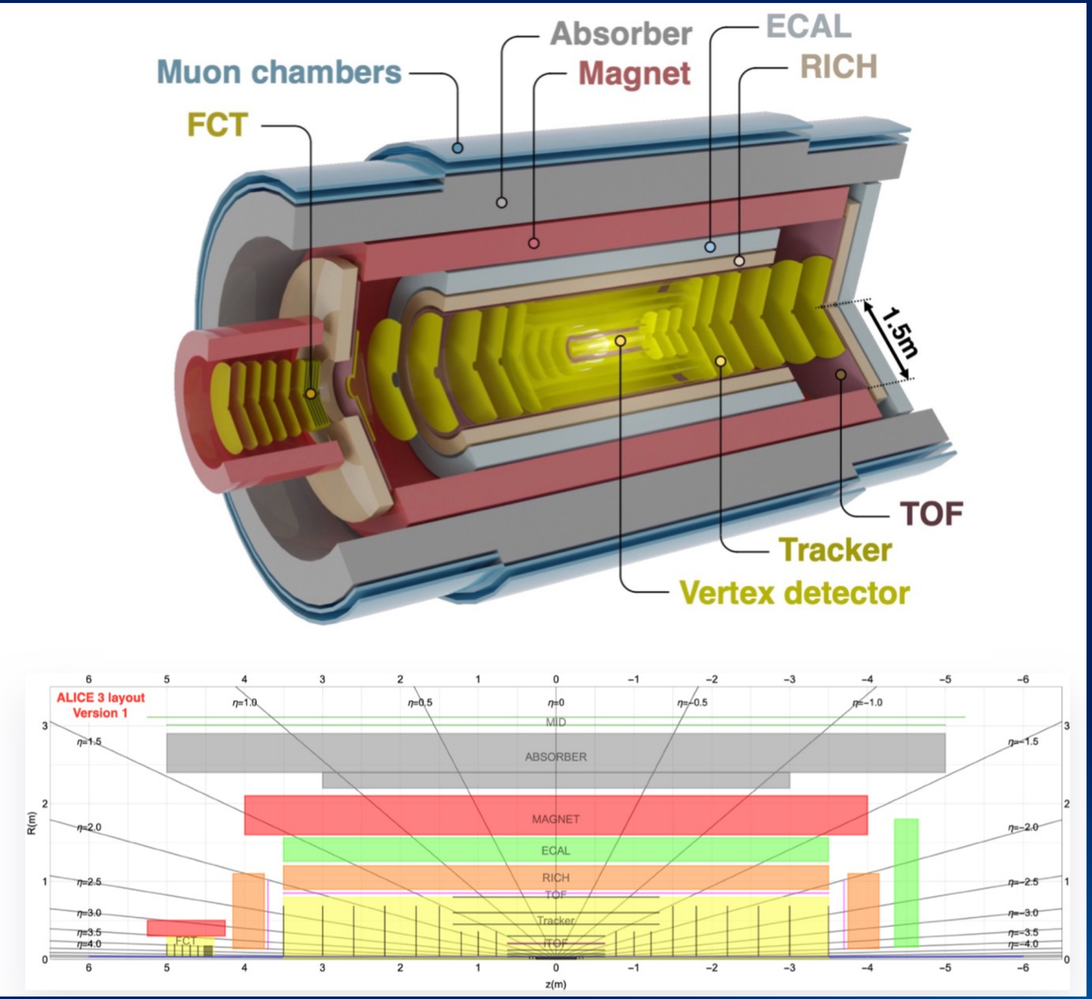


Such large separation between the signal and background at low kinetic energies makes $\overline{^3He}$ in space a very promising channel for the discovery of DM

Nature Physics 19, pages 61-71 (2023

Perspectives in light (hyper)nucleus studies

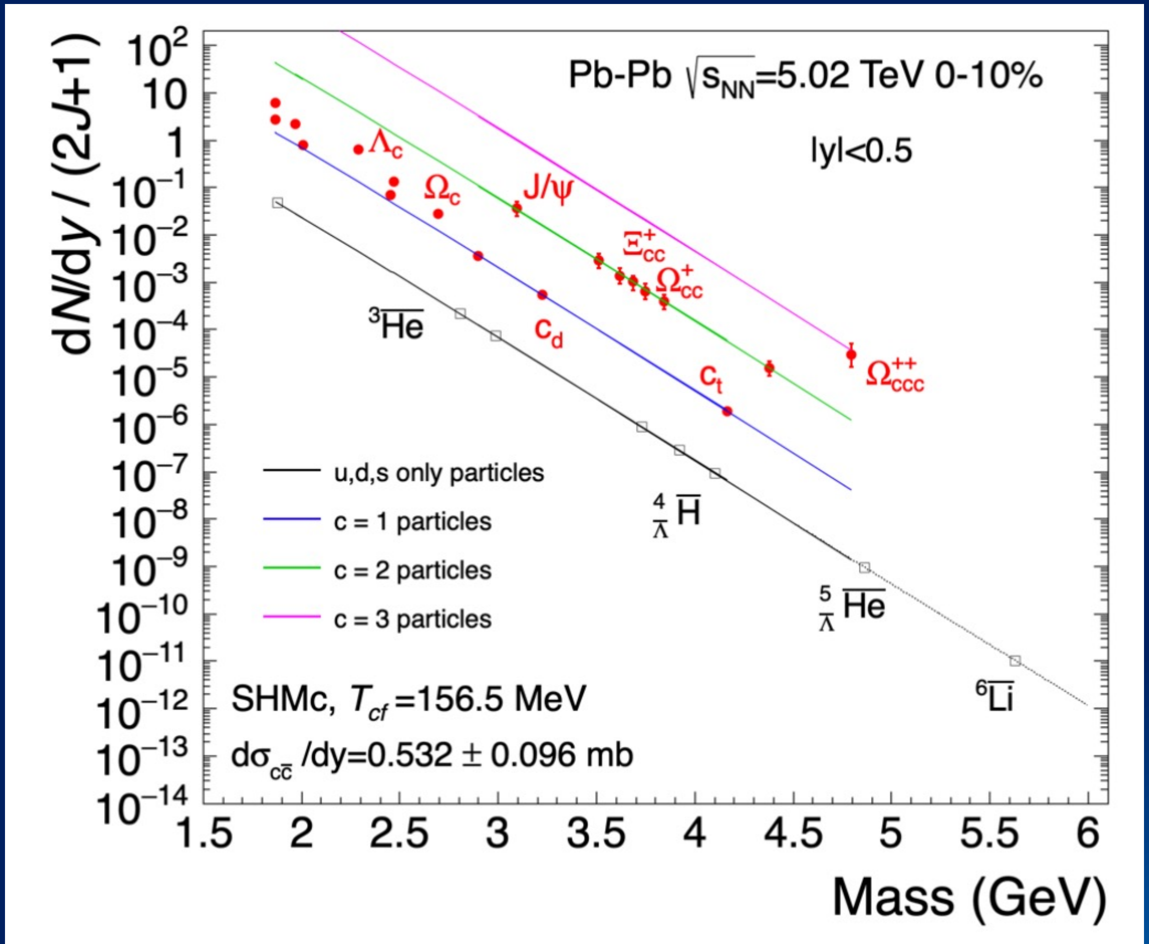
- Novel and innovative detector concept : ALICE3
- Excellent particle identification (hadrons and leptons)
- Tracking system
  - Compact and lightweight all-silicon MAPS tracker of ≈ 70 m^2
  - Retractable vertex detector
  - Large acceptance $|\eta| < 4$ (Barrel $|\eta| < 1.75$)
    - $\sigma_{DCA} \approx 10$ µm at p_T =200 MeV/c at $|\eta| < 1.75$
    - $\sigma_{DCA} \approx 30$ µm at p_T =200 MeV/c $1.75 < |\eta| < 4$
    - $\Delta p/p \approx$ 1-2%



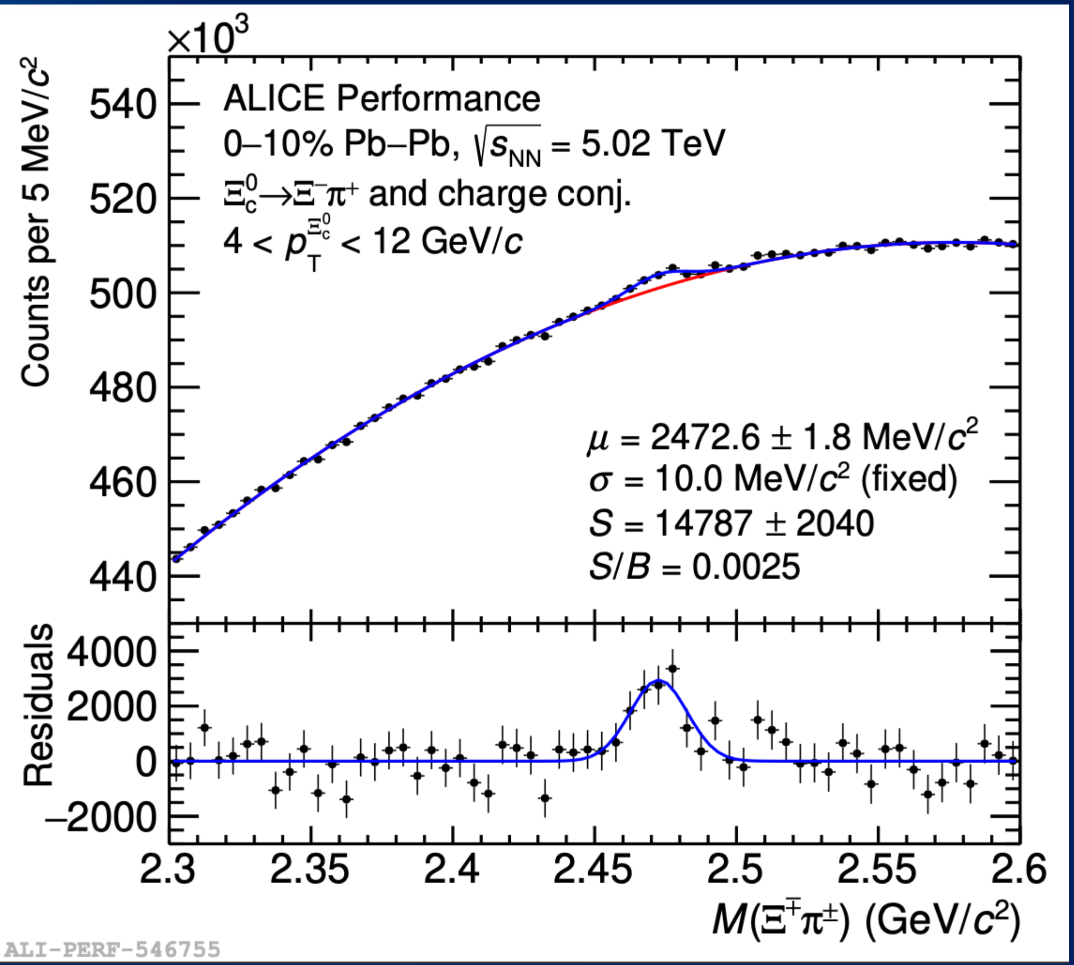
Search for exotic (anti-)(hyper-)(charm)-nuclei

- hyperon-nucleon interactions are poorly known and even less is known about the charmed-baryon nucleon interaction
- The ALICE 3 programme intends to shed light on these interactions with a set of unique measurements and potential discoveries in the area of exotic anti-, hyper-, and charm-nuclei
- The underlying production cross sections are poorly understood on the theoretical side. General lack of experimental data
  - SHM in Pb-Pb

https://arxiv.org/pdf/2211.02491



Search for exotic (anti-)(hyper-)(charm)-nuclei

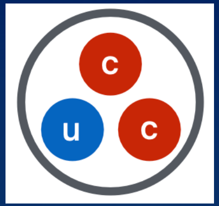


- Λ_c measurements in Pb-Pb accessible (see Phys. Lett. B 839 (2023) 13779)
- Heavier charmed-baryon measurements are challenging
  - Huge combinatorics of decay particles
  - $\Xi^0_c \rightarrow \Xi^- + \pi^+$
    - $\Xi^- \rightarrow \Lambda\pi^-$
      - $\Lambda \rightarrow p\pi$
- Measurements in Pb-Pb collisions in Run 3 are ongoing
- Improvements in the tracking and PID detectors will make both single charm and double charm baryons more accessible

Search for exotic (anti-)(hyper-)(charm)-nuclei

arXiv:2211.02491

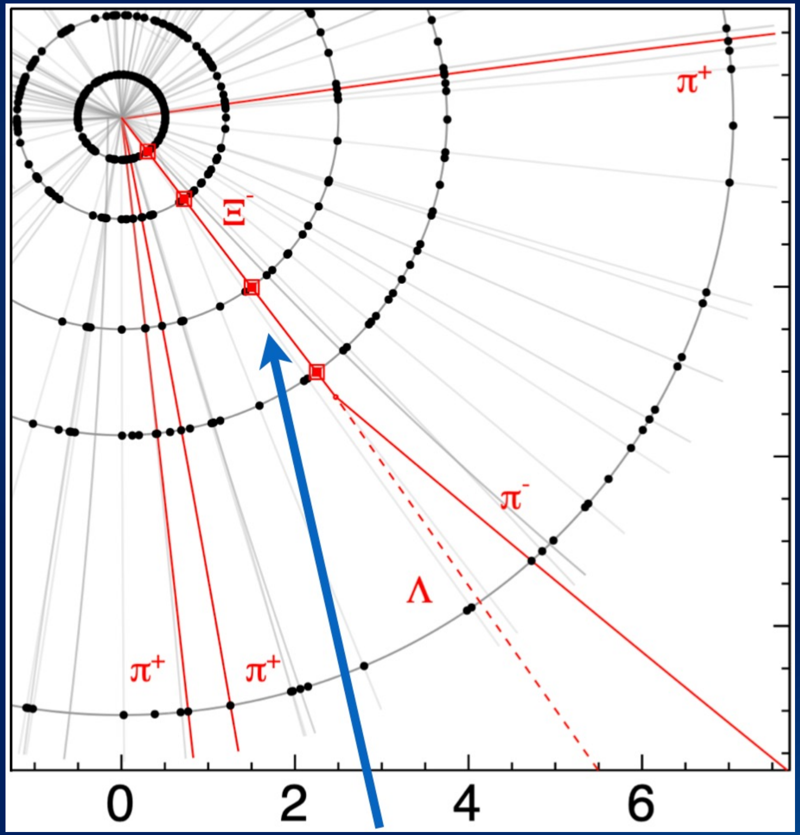
- c-deuteron $c_d \rightarrow d + K^- + \pi^+$ decay channel
- c-triton in the $c_t \rightarrow {}^3H + K^- + \pi^+$ decay channel
- hadronic interaction potentials e.g. Λ_c-p correlations
- Double charmed-baryons



$$\Xi_{cc}^{++} \rightarrow \Xi_c^+ + \pi$$

$$\Xi_c^+ \rightarrow \Xi^- + 2\pi^+$$

Multi-charmed baryons at low p_T: unique probe of hadron formation



Ξ^-

Strangeness tracking: direct tracking of Ξ^- in the barrel

Summary

- The ALICE experiment has performed several measurements in Pb-Pb, p-Pb and pp collisions, thus providing a wider look to the production mechanisms of light (anti)(hyper)nuclei
  - Provide useful information to understand the results from dark matter search experiments
- The production models of (anti)(hyper)nuclei describe different aspects of the production mechanisms but they still do not allow for a complete understanding of the full process
- Higher statistics in Run 3 and Run 4 will help to disentangle the different coalescence models and precision measurements will finally provide a clear understanding of the dynamics underlying nuclei formation dynamics
- A novel and innovative detector concept, namely ALICE3, will allow to access new measurements in the hyperon-nucleon interactions and especially to the charmed-baryon sector

Thank you